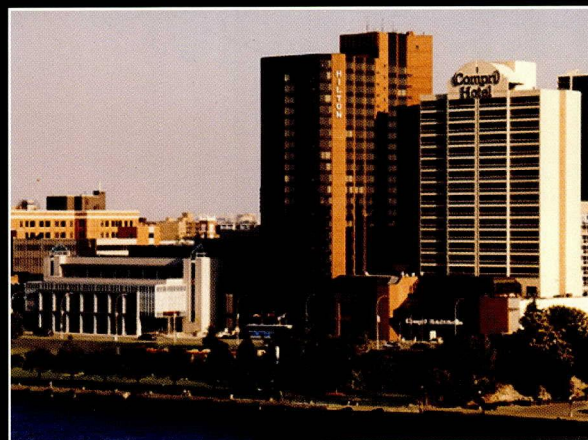


**May 31 to June 4 1998**

**16th International  
Technical Conference on the  
Enhanced Safety of Vehicles**

**Proceedings  
Volume 1 of 3**



The Cleary  
International Centre  
Windsor, Ontario  
CANADA

**ESV**  
WINDSOR98



# 16th International Technical Conference on the **Enhanced Safety of Vehicles** **Proceedings Volume 1 of 3**



U.S. Department  
of Transportation

National Highway  
Traffic Safety  
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**DOT HS 808 759**  
**October 1998**



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# Introduction

The United States Department of Transportation, National Highway Traffic Safety Administration (NHTSA), Office of Research and Development is the official government agency responsible for the implementation of the International Technical Conferences on the Enhanced Safety of Vehicles (ESV). The Conferences are held approximately every two years and hosted by participating Governments. Delegate and attendee participation includes worldwide governments, automotive industries, motor vehicle research engineers and scientists, medical, insurance, and legal professions, consumers, academia, private corporations, and international media.

The ESV Program originated in 1968 under the North Atlantic Treaty Organization (NATO) Committee on the Challenges of Modern Society, and was implemented through bilateral agreements between the governments of the United States, France, the Federal Republic of Germany, Italy, the United Kingdom, Japan, and Sweden. The participating nations agreed to develop experimental safety vehicles to advance the state-of-the-art technology in automotive engineering and to meet periodically to exchange information on their progress. Since its inception the number of international partners has grown to include the governments of Canada, Australia, the Netherlands, Hungary, Poland, and two international organizations -- the European Enhanced Vehicle-Safety Committee, and the European Commission. A representative from each country and organization serves as a Government Focal Point in support of the Conference.

In 1968 the Conference was known as the International Experimental Safety of Vehicles Conference. Over time, the focus of the Conference shifted from concentration on the development of experimental safety vehicles to broader issues of safety and international cooperation seeking reductions in motor vehicle fatalities and injuries. These issues include program advances such as Pedestrian Safety, Frontal and Side Impact Protection, Biomechanics, Intelligent Transportation Systems, and Vehicle Compatibility. In 1991, the participating governments agreed to change the name of the Conference to "The International Technical Conference on the Enhanced Safety of Vehicles" to reflect the current focus. The 14th ESV Conference, held in Munich, Germany, May, 1994, was the first conference in which the new name was used, and "25 Years of ESV Development" was celebrated.

The 15th ESV Conference, held in Melbourne, Australia, May, 1996, was precedence-setting as well. A new 5-year priority research program known as International Harmonized Research Activities (IHRA) was established under the auspices of the ESV Conference. The program established six international priority research areas; Biomechanics, Advanced Offset Frontal Crash Protection, Vehicle Compatibility, Pedestrian Safety, Intelligent Transportation Systems and recently chosen Side Impact Protection. In May of 1997, NHTSA hosted a Public Workshop to share with its partners the goals and objectives of IHRA. In November of 1997, the ESV Government Focal Points agreed that all participating governments would join in these priority research programs, and that the programs would be governed by an IHRA Steering Committee comprised mainly of the ESV Government Focal Points. Six Working Groups that now exist in each of the priority research areas are led by participating Governments, and are comprised of government and industry experts. The IHRA Steering Committee consisting of Government members meets biannually to review recommendations and research plans being developed by the Working Groups.

This, the 16th ESV Conference hosted by Transport Canada, held in Windsor, Ontario, Canada, May 31-June 4, 1998, was attended by delegates from twenty one (21) different countries. The IHRA Status Reports on the progress of the five priority research areas were presented during this Conference. Well over 300 technical papers were accepted for inclusion in the Conference Proceedings, with international authors representative of sixteen (16) different nations. This Conference also marked the first time scientific poster presentations were given.

The 17th ESV Conference, the first Conference of the 21<sup>st</sup> Century, will be held in Amsterdam, The Netherlands, in the year 2001. The year was chosen because IHRA will have met the 5-year deadline for reporting their vision, goals, objectives, and achievements under the program.

We thank our international conference participants for their continued interest, dedication and support. It is an outstanding example of the highest regard for automotive safety research we are certain will continue.



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Nissan Motor Company

**Masarul UEYAMA**  
National Research Institute of  
Police Science

**Shoji WATANABE**  
Ministry of International Trade  
and Industry

**Shinichi YAHAGI**  
Ministry of Transport

**Tsuyoshi YAMAGUCHI**  
Nissan Motor Company, Ltd.

**Takeshi YAMAJI**  
Tokyo Tire & Rubber Company

**Takenori YAMAMOTO**  
Honda R&D Company, Ltd.

**Toshimi YAMANOI**  
Nissan Motor Company, Ltd.

**Shigeyuki YAMAOKA**  
Nissan Motor Company, Ltd.

**Takeshi YAMAZAKI**  
Honda R&D Company Ltd.

**Masahiro YONETANI**  
Toyota Motor Corporation

**Suguru YOSHIDA**  
Honda R&D Company, Ltd.

## Korea\_\_\_\_\_

**Myung-Sik LEE**  
Daewoo Motor Company, Ltd.

## Poland\_\_\_\_\_

**Piotr PATORA**  
Bosmal

**Wojciech PRZYBYLSKI**  
Motor Transport Institute

**Cezary SZCZEPANIAK**  
Motor Transport Institute

## Spain\_\_\_\_\_

**Francesca SALA**  
IDIADA

**Joaquim HUGUET**  
IDIADA

## Sweden\_\_\_\_\_

**Per ANDERSSON**  
Autoliv Sverige AB

**Tommy ANDERSSON**  
Autoliv

**Jonas BARGMAN**  
Autoliv Research

**Peter BERGKVIST**  
SAAB Automobile AB

**Katarina BOHMAN**  
Autoliv Research

**Ola BOSTROEM**  
Autoliv Research

**Anders DJARV**  
Volvo Car Corporation

**Mikael EDVARDSSON**  
Volvo Car Corporation

**Rikard FREDIKSSON**  
Autoliv AB



# Delegates and Attendees (continued)

## Sweden\_\_\_\_\_

**Yngve HALAND**  
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**Soren HEDBERG**  
Swedish National Road  
Administration

**Erik HJERPE**  
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**Dagmar JEWKES-BUZEMAN**  
Chalmers University

**Lennart JOHANSSON**  
Volvo Car Corporation

**Per-Erik JOHANSSON**  
Autoliv Sverige AB

**Maria KRAFFT**  
Folksam Research

**Anders KULLGREN**  
Folksam Research

**Peter LARSSON**  
Swedish National Road  
Administration

**Per LENHOFF**  
SAAB Automobile AB

**Anders LIE**  
Swedish National Road  
Administration

**Martin LINDSSTROM**  
Autoliv

**Bjorn LUNDELL**  
Volvo Car Corporation

**Sigrun MALM**  
Folksam Research

**Anna MATTSODOTTER**  
Volvo Truck Corporation

**Hugo MELLANDER**  
TSRE

**Curt NORDGREN**  
BIL

**Johan NORDGREN**  
Autoliv Sverige AB

**Jan ODENMO**  
Autoliv

**Anders OHLUND**  
Volvo Car Corporation

**Jorgen PERSSON**  
Autoliv Sverige AB

**Hakan PETTERSSON**  
Autoliv Research

**Kåre RUMAR**  
Swedish Research Institute

**Ingrid SKOGSMO**  
Volvo Car Corporation

**Claes TINGVALL**  
Swedish National Road  
Administration

**Emma TIVESTEN**  
Volvo Car Corporation

**Anders YDENIUS**  
Folksam Research

## Switzerland\_\_\_\_\_

**Nicolas ROGERS**  
IMMA

## The Netherlands\_\_\_\_\_

**Hans AMMERLAAN**  
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**Gerard BLAAUW**  
TNO Crash Safety Research  
Centre

**Jan BUSSTRA**  
Ministry of Transport

**Kees DOORNHEIM**  
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Information Centre

**M.L. DUYNSTEE**  
Ministry of Transport

**Eric FICKEL**  
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**Erik FRATERMAN**  
TNO

**Riender HAPPEE**  
TNO

**Tom HEIJER**  
SWOV Institute for Road Safety  
Research

**Jeff HYUN**  
TNO MADYMO

**Robert KANT**  
TNO

**Henk LUPKER**  
TNO Automotive

**Gerard J.M. MEEKEL**  
RDW Vehicle Technology &  
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**Herman MOOI**  
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Centre

# Delegates and Attendees (continued)

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Centre

**Jan Paul PETERS**  
Yamaha Motor Europe N.V.

**Erwin POEZE**  
TNO

**B.G. REYS**  
TNO NL

**Tinkie SCHRAFFORDT KOOPS**  
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Information Centre

**Alexander STEENBRINK**  
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Centre

**Hans VAN DER BRUGGEN**  
RDW Department of Road  
Transport

**Rene VAN HAASTER**  
TNO MADYMO

**Boudewyn VAN KAMPEN**  
SWOV Institute for Road Safety  
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**Eric VAN OORSCHOT**  
TNO Crash Safety Research  
Centre

**Michiel VAN RATINGEN**  
TNO Crash Safety Research  
Centre

**Theo VERBRUGGEN**  
TNO MADYMO

**Robert W. N. WEGMAN**  
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**Jac WISMANS**  
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Centre

**Willem WITTEMAN**  
Eindhoven University of  
Technology

## United Kingdom\_\_\_\_\_

**Berni ALLAN-STUBBS**  
Motor Industry Research  
Association

**Gordon BACON**  
Motor Industry Research  
Association

**Andy BARNES**  
Ogle TNO Safety Products

**Ian BODGER**  
Millbrook Proving Ground

**Mo BRADFORD**  
Vehicle Safety Research Centre

**Jamie BUCHANAN**  
Motor Industry Research  
Association

**Bryan CANNON**  
Rover Group

**Robert DAVIES**  
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Association

**Mervyn EDWARDS**  
Transport Research Laboratory

**Paul FAY**  
Ford Motor Company

**Richard FRAMPTON**  
VSRC Loughborough  
University

**Steve GILLINGHAM**  
Department of the Environment  
Transport and The Regions

**John GREEN**  
Rover Group

**Geoff HARVEY**  
Department of the Environment  
Transport and The Regions

**Matthew HILLAM**  
Millbrook Proving Ground

**Adrian HOBBS**  
Transport Research Laboratory

**Fred HOPE**  
Hope Technical Development

**Robert HOPE**  
Hope Technical Development

**Jim HOPTON**  
Motor Industry Research  
Association

**Ian HORTON**  
Rover Group

**Saad JAWAD**  
University of Hartfordshire

**Allan JONES**  
Jaguar Cars

**Dusan KECMAN**  
Cranfield Impact Centre

**Tony LAWSON**  
Motor Industry Research  
Association

# Delegates and Attendees (continued)

## United Kingdom\_\_\_\_\_

**James LENARD**  
ICE Ergonomics

**Michael LEWIS**  
Rolls-Royce Motor Cars  
Limited

**Richard LOWNE**  
Transport Research Laboratory

**Murray MACKAY**  
University of Birmingham

**Paul MANNING**  
University of Nottingham

**Matsudaira KATSUTOSHI**  
Honda R&D Company

**John McMASTER**  
University of Nottingham

**Roy MINTON**  
Transport Research Laboratory

**Pat MURRAY**  
University of Manchester

**Charles OAKLEY**  
Transport Research Laboratory

**Peter O'REILLY**  
Department of the Environment  
Transport and The Regions

**Clare OWEN**  
Transport Research Laboratory

**Andrew PARKES**  
University of Leeds

**Chris PATIENCE**  
The Automobile Association

**Ian PATON**  
Middlesex University

**Tony PAYNE**  
Motor Industry Research  
Association

**Adrian ROBERTS**  
Transport Research Laboratory

**Ken ROBERTS**  
The Motor Insurance Repair  
Research Centre

**Keith RODGERS**  
Department of the Environment  
Transport and the Regions

**Peter ROY**  
Middlesex University

**Majid SADEGHI**  
Cranfield Impact Centre

**Stu SHOWLER**  
Ford Motor Company

**Michael SMITH**  
The Motor Insurance Repair  
Research Centre

**Alan THOMAS**  
FFA Jaguar Research

**Pete THOMAS**  
ICE Ergonomics

**Kazunori TOMIMATSU**  
Nissan-NETC

**W. Angus WALLACE**  
University of Nottingham

**Julian WARREN**  
Honda R&D Company

**Roger WORTH**  
Department of the Environment  
Transport and the Regions

**Peter WRIGHT**  
F.I.A.

**Nial WYKES**  
Transport Research Laboratory

## United States\_\_\_\_\_

**Julie ABRAHAM**  
National Highway Traffic Safety  
Administration

**Ed ABRAMOSKI**  
Ford Motor Company

**Ismat A. ABU-ISA**  
General Motors Corporation

**Krish AEKBOTE**  
EASI Engineering (FORD)

**Wade ALLEN**  
Systems Technology, Inc.

**Kristy ARBOGAST**  
Childrens Hospital of  
Philadelphia

**Steve ARNDT**  
Safety Engineering & Forensic  
Analysis

**Jeffrey AUGENSTEIN**  
University of Miami

**Tom BALOGA**  
Britax Child Safety

**Tina BARBAROVIC**  
ABC News

**Saeed BARBAT**  
Ford Motor Company

**John BARIL**  
CBS News



# Delegates and Attendees (continued)

## United States\_\_\_\_\_

**Manuel BARTOLO**  
Ford Motor Company

**John BAUER**  
TRW

**Mark BAYKIAN**  
NBC News

**Don BEARDEN**  
Subaru of America

**Jeffrey BERLINER**  
Chrysler Corporation

**Al BERNAT**  
Takata

**Sukhbir BILKHU**  
Chrysler Corporation

**David BISS**  
Automotive Safety Analysis  
Corporation

**Jay BLACKMAN**  
NBC News

**Byron BLOCH**  
Auto Safety Design

**Curel S. BOETTCHER**  
General Motors Corporation

**Jennifer L. BOHLEN**  
TRW

**James R. BOLAND**  
Ford Motor Company

**Ron BOLTZ**  
Chrysler Corporation

**Jeff BORCHARDT**  
General Motors Corporation  
Small Car Group

**Noble BOWIE**  
National Highway Traffic  
Safety Administration

**Keith BRADSHER**  
The New York Times

**David S. BREED**  
Automobile Technical  
International

**Jim BRITELL**  
National Highway Traffic  
Safety Administration

**Warren BROWN**  
Washington Post

**Majeed BSHATTI**  
General Motors Corporation

**August BURGETT**  
National Highway Traffic  
Safety Administration

**Paul BUTLER**  
Ford Auto Safety Office

**Lou CAMP**  
Ford Motor Company

**Kirsten CARR**  
Ford Motor Company

**Tom CARR**  
American Automobile  
Manufacturers Association

**Wichai CHARA**  
Toyota Technical Centre

**Alan CHEALE**  
VDO North America

**James CHENG**  
Ford Motor Company

**Clifford C. CHOW**  
Ford Motor Company

**Frank CHRIST**  
Biodynamic Research  
Corporation

**Susan CISCHKE**  
Chrysler Corporation

**Juanito CO**  
Ford Motor Company

**Daniel S. COHEN**  
MITRETEK

**Ken COLE**  
Detroit News

**Terry CONNOLLY**  
General Motors Corporation

**Brian CORBETT**  
Ward's Automotive Reports

**Greg DANA**  
Association of International  
Automobile Manufacturers

**Rich DEERING**  
General Motors Corporation

**Nathan DELSON**  
Yale University

**Yih-Chaing DENG**  
General Motors Corporation

**Duane DETWILER**  
Honda R&D Americas

**Kennerly DIGGES**  
George Washington University

**Brian DOERFLINGER**  
CBS News

# Delegates and Attendees (continued)

## United States \_\_\_\_\_

**Jiamao DOONG**  
Ford Motor Company

**Stefan DUMA**  
U.V.A. Automobile Safety

**William F. EAGLESON**  
Ford Motor Company

**Ali ELHAGEDIAB**  
General Motors Corporation

**Norman ELLSWORTH**  
Magna International

**Uli ELTER**  
General Motors Corporation  
International Operations

**Bruce ENDERLE**  
Yamaha Motor Corporation

**Rolf EPPINGER**  
National Highway Traffic  
Safety Administration

**Leonard EVANS**  
General Motors Corporation

**Bruce FARR**  
Simula Automotive Safety  
Devices

**Barry FELRICE**  
American Automobile  
Manufacturers Association

**Jim FEUSTEL**  
Ford Motor Company

**Michael FINKELSTEIN**  
Finkelstein & Associates

**Maggie FISHER**  
Delphi Automotive Systems

**Bill FLEMING**  
TRW Vehicle Safety

**Stephan FRICK**  
The Woodbridge Group

**Donald FREIDMAN**  
Friedman Research

**Ichiro FUKUMOTO**  
Toyota

**Motoya FUNATSU**  
Toyota Technical Centre

**Patricia FYHRIE**  
General Motors Corporation

**Hampton C. GABLER**  
National Highway Traffic  
Safety Administration

**Domenico GABRIELLI**  
Ford Motor Company

**Tim GANDEE**  
Takata

**Mark GARCIA**  
Autoliv North America

**Ed GARSTEN**  
CNN News

**Elizabeth GARTHE**  
Garthe Associates

**Ann GILKEY**  
General Motors Corporation

**Jim GILL**  
ITT Automotive

**Donna E. GILMORE**  
National Highway Traffic  
Safety Administration

**Anne GINN**  
General Motors Corporation

**Jackie A. GOFF**  
U.S. Department of  
Transportation

**Bob GOLDENTHAL**  
Chrysler Corporation

**Jeff GOLDMAN**  
CBS News

**Madan GOPAL**  
Delphi Automotive Systems

**Stan GORNICK**  
Orion Bus Industries

**Herb GOULD**  
U.S. Department of  
Transportation Volpe Center

**Bill GOUSE**  
Freightliner Corporation

**Jeff GREEN**  
Ward's Automotive Reports

**Gary GREIB**  
Delphi Automotive Systems

**Charles J. GRISWOLD**  
C.J. Griswold

**Ernie GRUSH**  
Ford Motor Company

**Tom GUTWALD**  
First Technology Safety  
Systems

**Dietmar HAENCHEN**  
Volkswagen of America

**Mark HAFFNER**  
National Highway Traffic Safety  
Administration

**Alena HAGEDORN**  
Transportation Research Center

# Delegates and Attendees (continued)

## United States \_\_\_\_\_

**Robert HAGER**

NBC News

**Mike HAGUE**

Breed Technologies

**Chet HALE**

American Honda Motor  
Company

**Heather HALLENBECK**

Transportation Research Center

**Gordon HARD**

Consumer Reports

**Warren HARDY**

University of Michigan

**Lindsay HARRIS**

Fisher-Price

**Phil HASELTINE**

American Coalition for Traffic  
Safety

**Noriyuki HAYAMIZU**

Wayne State University

**Simon HE**

Breed Technologies

**Sherman HENSON**

Ford Motor Company

**Kazuo HIGUCHI**

Honda North America

**Donald G. HILLEBRAND**

Chrysler Corporation

**John HINCH**

National Highway Traffic  
Safety Administration

**Margaret HINES**

Ohio State University

**Ralph HITCHCOCK**

American Honda Motor  
Company

**W. Thomas HOLLOWELL**

National Highway Traffic  
Safety Administration

**Samuel HONG**

Insurance Services Office

**Tim HOYT**

Nationwide Insurance

**Don HUELKE**

University of Michigan  
Transportation Research Center

**Bob HULTMAN**

Ford Motor Company

**Richard HUMPHREY**

General Motors Corporation

**Annette IRWIN**

General Motors Corporation

**Ryosuke ITAZAKI**

Japan Automobile Standards  
Internationalization Center

**Tetsuo ITO**

Furukawa Electric

**Toshi ITO**

Nissan Motor Company R&D

**Takekazu IWATA**

Consulate General of Japan

**Masao IZUMI**

KANTUS Corporation

**Sujit JAIN**

Denso International America

**John JENKINS**

Transportation Research Center

**Jack JENSEN**

General Motors Corporation

**Natalie JEREMIVENKO**

Yale University

**Amin JIBRIL**

Ford Motor Company

**H. George JOHANNESSEN**

Omnisafe Incorporated

**Steve JONAS**

Volkswagen of America

**Bob JONES**

Delphi Automotive Systems

**Michael P. KACZMAR**

Joalto Design Incorporated

**Joseph KANIANTHRA**

National Highway Traffic Safety  
Administration

**Sunny KANKANACA**

University of Michigan

**B.H. KANTOWITZ**

Battelle Seattle Research Center

**Jim KARLOW**

Takata

**Jim KAUFFMAN**

CNN News

**Tim KEER**

ARUP

**Rich KEMPF**

Navistar International  
Transportation

**Michael KERMAN**

The Woodbridge Group

# Delegates and Attendees (continued)

## United States \_\_\_\_\_

**Daniel L. KERSHNER**  
John Hopkins University

**Anil KHADILKAR**  
Biodynamics Engineering

**Ray KIEFER**  
General Motors Corporation

**Agnes KIM**  
Ford Motor Company

**Albert I. KING**  
Wayne State University

**Bill KING**  
Ford Motor Company

**Don KING**  
The Polk Company

**Bill KINIRY**  
Piper & Marbury

**Sarah KIRKISH**  
Ford Motor Company

**Naoki KIUCHI**  
First Technology Safety  
Systems

**Theodore A. KLAUS**  
Honda R&D Company, Ltd.

**Mike KLEINBERGER**  
National Highway Traffic  
Safety Administration

**Richard L. KLIMISCH**  
American Automobile  
Manufacturers Association

**Robert KLINCK**  
Morgan, Melhuish, Monaghan,  
Arvidson, Abrutyn & Lisowski

**Kathy KLINICH**  
University of Michigan  
Transportation Research Center

**Haruhiko KONDO**  
Nissan North America

**Doug KONONEN**  
General Motors Corporation

**Gregory W. KOSTYNIUK**  
Chrysler Motor Corporation

**Lidia KOSTYNIUK**  
University of Michigan  
Transportation Research  
Institute

**Scott KRENICH**  
Biodynamic Research  
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**Dave KRUSCHECK**  
ABC News

**Bill KUBOTZ**  
CBS News

**Ed KUCZYNSKI**  
The Woodbridge Group

**Shashi KUPPA**  
Conrad Technologies,  
Incorporated

**Robert C. LANGE**  
General Motors Corporation

**Ian LAU**  
General Motors Corporation

**Drew LEVINSON**  
CBS News

**Richard LEWIS**  
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**Wenyl LIAN**  
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**John LISOWSKI**  
Morgan, Melhuish, Monaghan,  
Arvidson, Abrutyn & Lisowski

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**Johanna LOWRIE**  
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**Adrian LUND**  
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**Tony MAGDALENO**  
General Motors Corporation

**Cindy MALIS**  
CNN News

**Miriam MANARY**  
University of Michigan

**Nicholas MANGO**  
Garthe Associates

**Joe MANNING**  
Simula Technologies

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Isuzu Motors America

**Joe MARSH**  
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# Delegates and Attendees (continued)

## United States \_\_\_\_\_

**Artie MARTIN**  
General Motors Corporation

**Ricardo MARTINEZ, M.D.**  
National Highway Traffic  
Safety Administration

**Christy MCKENDREW**  
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**John MELVIN**  
General Motors Corporation

**Bud MERTZ**  
General Motors Corporation

**Susan MEYERSON**  
Insurance Institute for Highway  
Safety

**Ed MICHEL**  
Harley-Davidson Motor  
Company

**Richard MILLER**  
CBS News

**Earl MILLOY**  
CBS News

**Zohir MOLHEM**  
General Motors Corporation

**Robert J. MOLLOY**  
National Transportation Safety  
Board

**Ed MOORE**  
CBS News

**George MOORE**  
Delphi Automotive

**Jamie MOORE**  
University of Michigan  
Transportation Research  
Institute

**Mike MORELLI**  
The Woodbridge Group

**Richard M. MORGAN**  
National Highway Traffic  
Safety Administration

**Ken MORMAN**  
Ford Motor Company

**Christina MORRIS**  
Insurance Institute for Highway  
Safety

**Steve MOSS**  
First Technology Safety  
Systems

**Greg MOWRY**  
Simula Automotive Safety  
Devices

**William MU**  
TRW

**Takayuki NAGAI**  
Denso International America

**Said NAKHLA**  
Breed Technologies

**Gopal NARWANI**  
JAT

**Donald NAUSS**  
LA Times

**George NEAT**  
U.S. Department of  
Transportation Volpe Center

**Tuan NGO**  
General Motors Corporation

**Guy NUNSHOLTZ**  
Chrysler Corporation

**Chris O'CONNOR**  
Ford Motor Company

**Linda L. O'CONNOR**  
NHTSA (Consultant)

**Sue OHARA**  
Mitsubishi R&D America

**Yaichi OISHI**  
Toyota Technical Center

**Yuji OKUDA**  
First Technology Safety  
Systems

**Barbara O'NEILL**  
Denso International America

**Brian O'NEILL**  
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Safety

**Bob ORR**  
CBS News

**Hiro OTSUKI**  
Denso International America

**Raymond P. OWINGS**  
National Highway Traffic Safety  
Administration

**Brian PARK**  
National Highway Traffic Safety  
Administration

**George PARKER**  
Association of International  
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**Rasik N. PATEL**  
Ford Motor Company

**Elana PERDECK**  
University of Miami

# Delegates and Attendees (continued)

## United States \_\_\_\_\_

**Mike PEREL**

National Highway Traffic  
Safety Administration

**Helen PETRAUSKAS**

Ford Motor Company

**Elaine PETRUCELLI**

Association for Advancement of  
Automotive Medicine

**Sandy PETRYKOWSKI**

ABC News

**Jeffrey PIKE**

Ford Motor Company

**Gordon PLANK**

U.S. Department of  
Transportation Volpe Center

**Jerry PLANTE**

SAAB Cars USA

**Priya PRASAD**

Ford Motor Company

**Aloke PRASAD**

National Highway Traffic  
Safety Administration

**Howard PRITZ**

National Highway Traffic  
Safety Administration

**Jim PYWELL**

General Motors Corporation

**Carl RAGLAND**

National Highway Traffic  
Safety Administration

**Glen RAINS**

National Highway Traffic  
Safety Administration

**Nagarajan RANGARAJAN**

GESAC

**Martin RAPAPORT**

Volvo Cars of North America

**Philip RECHT**

National Highway Traffic  
Safety Administration

**Don REED**

Automotive Engineering  
Magazine

**Matt REED**

University of Michigan  
Transportation Research Center

**Bob RICCI**

U.S. Department of  
Transportation Volpe Center

**Leda RICCI**

University of Michigan

**Stephen RIDELLA**

TRW Vehicle Safety

**Vernon ROBERTS**

National Transportation Safety  
Board

**Elizabeth ROSS**

Ford Motor Company

**Gary ROSSOW**

Freightliner Corporation

**Steve ROUHANA**

General Motors Corporation

**Raj ROYCHOUDHLLRY**

Delphi

**Michael RUSSELL**

National Highway Traffic  
Safety Administration

**Jesse RUAN**

Ford Motor Company

**Kenneth RUTLAND**

National Highway Traffic Safety  
Administration

**Toshiaki SAKURAI**

Mitsubishi Motors

**Randa Radwan SAMAHA**

National Highway Traffic Safety  
Administration

**Jeffrey SANTROCK**

General Motors Corporation

**Roger SAUL**

National Highway Traffic Safety  
Administration

**Mick SCHERBA**

General Motors Corporation

**Risa SCHERER**

Ford Motor Company

**Greg SCHMELING**

Harley-Davidson Motor  
Company

**Scott SCHMIDT**

Land Rover

**Larry SCHNEIDER**

University of Michigan

**Don SCHOMER**

ARCO Chemical

**Peter SCHUSTER**

Ford Motor Company

**Don SCHWENTKER**

Regulatory Consultant

**Peter SCHWERDTMANN**

ITT Automotive

**Bill SCULLY**

Bavarian Motor Works

# Delegates and Attendees (continued)

## United States \_\_\_\_\_

**John SEIPP**  
Seipp, Flick & Kissane

**Dan SELKE**  
Mercedes-Benz of North  
America

**Mino SHAH**  
Delphi Automotive Systems

**Bill SHAPIRO**  
Volvo Cars of North America

**Phil SHEETS**  
Kawasaki Motors Corporation

**Mike SHEH**  
Silicon Graphics

**Bob SHELTON**  
National Highway Traffic  
Safety Administration

**Linda SHERMAN**  
L.S. Sherman Consulting

**Toyohiko SHINDO**  
Honda R&D North American,  
Incorporated

**Fred SHOKOOHI**  
Autoliv ASP

**Paul SIMPSON**  
General Motors Corporation

**Albert SLECHTER**  
Chrysler Corporation

**Heather E. SMITH**  
Conrad Technologies  
Incorporated

**James K. SPRAGUE**  
Exponent

**Ram SRIRAM**  
Ford Motor Company

**Michael STANDO**  
Ford Motor Company

**Lisa STARK**  
ABC News

**John STATES**  
National Center for Injury  
Prevention & Control

**Mike STEINWACHS**  
Fisher-Price

**Mark STENDER**  
Ford Motor Company

**Harry STOFFER**  
Automotive News

**Rob STRASSBURGER**  
Nissan North America

**Catherine STRONG**  
The Associated Press

**Sheldon STUCKI**  
National Highway Traffic  
Safety Administration

**Thiag SUBBIAN**  
Ford Motor Company

**John SULLIVAN**  
Ford Motor Company

**Lori SUMMERS**  
National Highway Traffic  
Safety Administration

**Doug SUSALLA**  
ABC News

**Nobuhiko TAKAHASHI**  
Nissan Motor Company

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Luigi Cicinnati  
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Japan Automobile Manufacturers Association, Inc.  
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Porsche AG

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National Highway Traffic Safety Administration

Jeff Elias

Transportation Research Center

Greg Mowry

Simula Automotive Safety Devices Incorporated

United States

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- Design and Development of an Advanced Lower Extremity: ALEX II** ..... 1910

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Transportation Research Center Inc.

Howard B. Pritz

National Highway Traffic Safety Administration

Michael S. Beebe

Applied Safety Technology Corporation

United States

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R. Happee, R. van Haaster

TNO Crash-Safety Research Centre

The Netherlands

L. Michaelsen, R. Hoffmann

EASi Engineering GmbH

Germany

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University of Virginia

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The Motor Industry Research Association

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Alan Thomas

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United Kingdom

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Japan Automobile Research Institute (JARI)	
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National Highway Traffic Safety Administration	
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Daihatsu Motor Company, Ltd.	
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Kyoto University	
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Transport Research Laboratory	
United Kingdom	
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Biokinetics and Associates, Inc.	
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The University of Western Australia Road Accident Prevention Research Unit  
Australia

# Opening Ceremonies

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## Welcoming Remarks

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### Nicole Pageot

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Director General  
Road Safety and Motor Vehicle Regulation  
Transport Canada  
Canada

Ms. Pageot, as Conference co-chairperson, began by thanking the sponsors, delegates and attendees. She stated she was delighted Transport Canada had the opportunity to host the 16<sup>th</sup> ESV Conference in Windsor and hoped that everyone would partake in the beauty of the city. Ms. Pageot then introduced the Conference co-chairperson and sponsor, Dr. Raymond P. Owings, Associate Administrator, National Highway Traffic Safety Administration.

### Raymond P. Owings, Ph.D.

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Associate Administrator  
National Highway Traffic Safety Administration  
United States

Thank you Nicole. Minister Collenette, Dr. Martinez, distinguished guests, ladies and gentlemen. It is an honor and distinct privilege for me to co-chair this technical conference with Ms. Nicole Pageot, to explore new and innovative motor vehicle safety research opportunities.

I would first like to express my appreciation to Transport Canada for hosting this important event and to the City of Windsor for their warm hospitality. Also, to you the authors and delegates, I extend a warm welcome and thank you for being a part of this international exchange. Sixteen nations will be represented during this conference by way of oral presentations, poster presentations and written papers.

This, the 16th ESV Conference, will mark the end of the millennium for this forum. The next time this group comes together we will have entered the 21<sup>st</sup> Century. It is our hope at the National Highway Traffic Safety Administration that the new century will lead us to the road to zero fatalities, not only in the United States, but for our global partners as well. We at DOT believe the ESV Conference is a vital part of this road. Perhaps the best testimony to this can be found in the words of Professor Praxenthaler eighteen years ago during his welcoming address to the delegates of the 8th ESV Conference. And I quote "These conferences have a tradition which has caused experts and automobile users alike to listen rather

carefully; ...these conferences generate initiatives - and if it were possible to trace their complex routes - we would learn that these initiatives have saved many lives and reduced injuries." end quote.

It is through the vital work and expertise of you, the researchers, engineers, and doctors, through commitment of you, the decision-makers; through you, the academia who ensure that this science does not die in our educational institutions, and through our recently initiated harmonized research activities, that we all will continue to save lives and reduce injuries globally.

For the past two years, we at the National Highway Traffic Safety Administration have been working with our host Transport Canada, to again bring you the most scientifically sound technical conference. We set a record for this conference - over 300 technical abstracts were submitted for consideration. We are thankful to the ESV Government Focal Points, and the Technical Session Chairmen for their diligence in making selections for oral and poster presentations. This is never an easy task. This conference marks the first time poster presentations will be on display. I encourage you to visit the displays and provide feedback.

On behalf of the government of the United States, I welcome you to the 16th ESV Conference.

Thank you.

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# Keynote Addresses

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## Ricardo Martinez, M.D.

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Administrator  
National Highway Traffic Safety Administration  
United States

Good morning. Thank you Minister Collette, Ms. Pageot, Dr. Owings and all of you. I bring greetings from the United States Secretary of Transportation Rodney E. Slater.

Secretary Slater sends his regrets, but wants you to know that safety is his top priority and the top transportation priority in the United States. It is our North Star, by which we are guided in all our transportation decisions. He wishes you a successful and enlightening conference.

What an exciting and most opportune time for us to come together. Vehicle safety is, and will always remain, a high priority for everyone in this room. But as we loom on the cusp of a new millennium, we must understand the challenges of today and turn them into the opportunities of tomorrow.

Four years ago at NHTSA, we committed ourselves to doing just that. With our fatality rate, seat belt use and drunk driving statistics stagnant, we realized that the easy gains in traffic safety had been made and that we had three big options to achieve further success: big government, big budget, and big change. We knew that big change was the best answer.

Working as a team, we made NHTSA fast, friendly, and flexible with an outward focus. We recognized that information is a perishable commodity and worked to develop an international research agenda that would leverage all of our resources and speed the creation of knowledge and development of solutions.

We took a look at our partners and realized we were limiting our involvement to a small segment of those that could help. Safety is not just an industry problem and it is not just a government problem – it is **everyone's** problem. We engaged and mobilized others – traditional and nontraditional partners at the national and international levels. We have lit a fire and we want it to spread.

By putting a human face on the safety issue – we are showing America that everyone has a responsibility to find solutions to this problem. Safety is not about protecting dummies, but about saving people.

We are now focusing on safety for the right reasons. It is not just a regulatory issue, or a cost issue,

or a legal issue. It is, and always has been about people saving people.

The lessons we have learned at NHTSA over the past four years have relevance to this esteemed group at this premier safety conference. For you, I have a simple message: Opportunity knocks.

The traditional approach has been to focus exclusively on the crashworthiness of the vehicle. This has led to tremendous advances in safety and, as a physician, I have seen people survive in crashes that previously would have been fatal.

But, so too for the vehicle, many of the easy gains have been made. What will the next ESV conference and the next century bring forward as safety advances?

There are three clear steps we must take: broaden the scope of our approach, expand the dialog with others, and create the tools and resources to support these changes.

We must broaden the scope beyond crashworthiness to focus technologies on crash avoidance and post-crash injury control. Among other things, crash avoidance technologies provide early warning systems, navigational aids, enhanced visibility and hazard notification, assisted braking and steering systems, and delivery of information and communications. With 90 percent of crashes caused by human actions, crash avoidance clearly has an enormous payoff, yet it is unclear if emerging systems will decrease or increase the task of driving.

It is an unfortunate truth that we know more about the vehicle than the human in it. At the same time that we are aging as a population, we are adding information systems and sophisticated technology to the driving task. We must know much more about the "Human-machine interface" if we are to optimize these systems.

Minimizing the seriousness of an injury after a crash often depends on early access to medical care. More than half of all fatal crashes in America are single vehicle and in a rural environment. In the chain of survival, delays in discovery, access to communications and accurate notification of medical responders diminishes a crash victim's chance of survival. In

emergency medicine, we say "time is tissue." Again, using technology, we can eliminate these delays and extend the medical safety net to those who need immediate help.

NHTSA's Automated Collision Notification (ACN) system technology is already being tested in 500 vehicles in Buffalo, New York and could be available nationwide within five years. Six crashes have happened to date and the box worked properly in all cases, sending global positioning system coordinates, direction and force of impact, and calculating a probability of injury. But to work, the emergency medical system must be able to receive the calls and use the information. We are working with multiple partners to build the receiving communications and dispatch network.

Both these opportunities for saving lives are practical and doable, but neither can be done by just those in this room. Pre-crash and post-crash, and even the crashworthiness, technologies require us to expand the dialog to others and create a "living link" with other professional disciplines. For example, crash avoidance engineers should integrate with specialists in aging, vision, rehabilitation, mental cognition, and neuropsychology. Vehicle crashworthiness engineers should integrate with medical researchers, practitioners, and rehabilitationists. Post-crash engineers should integrate with emergency responders, dispatchers, and medical providers.

We cannot be insular and isolated in our knowledge in a world of flowing information. The interface between knowledge disciplines is critically important. When sharp divisions occur between disciplines, knowledge falls through the cracks and is lost or missed. When boundaries overlap, we create a safety net for people and stimulate innovation and creativity.

Lastly, we are already creating the tools to build our bridge to the future. The National Advanced Driving Simulator (NADS) is the next generation of simulators and will be the most advanced and sophisticated in the world when it is completed next year. It takes us closer to real world driving conditions than any before it.

We talk about putting a black box in cars – but the real black box is the human being. NADS helps us understand that human/vehicle interface and will help us better understand how humans respond at the limits of performance without truly putting them in harms way. We will also use NADS to study the human/environment interface by generating various road, intersection, and signage designs under a variety of conditions. Fabrication has begun and hope to be

operational in March, year 2000.

The Crash Injury Research and Engineering Network (CIREN) links seven trauma centers, from across the country, to engineers in the labs in order to study the cause, effects and results of real world crashes.

CIREN centers have multidisciplinary teams of physicians, medical researchers, safety engineers, crash reconstructionists, public safety professions, and others who review the crash and the patients.

CIREN brings us back to our basic concept of creating a living link between those that take care of injuries and those that design the vehicles. We must always keep one foot in the crash lab and one foot in the real world.

To sustain our progress in vehicle safety, we cannot afford to have our medical personnel taking care of injuries without understanding what happened in the crash. We cannot have our engineers developing and designing systems without understanding the variability of both real world crashes and their occupants.

CIREN allows us to go from the field to the facility to the drawing room.

I encourage all of you to create strong relationships with your trauma centers, emergency departments and rehabilitation centers in your own areas. Have your staff rotate through them on a regular basis. My staff routinely visit these centers throughout the country because they are our learning forum. That is where our customers are.

With these technologies we have an opportunity to break new ground and open the doors to new knowledge that can be used to improve public health and safety.

Working with national and international partners, like many of you here today, we will continue to advance the safety issue.

It is about asking the right questions. And looking around the room, I have to ask a question – are all the right people here to help bring us into the new millennium – to help solve the safety issues of the 21<sup>st</sup> century?

If not, we need to rethink and review our mailing list right after this meeting is over. We want to continue to create the tools and resources, to engage, energize and mobilize all our constituents.

And let me say, "thank you" to all of you. As Administrator, emergency physician and particularly as a father, I know there are few things I can control regarding the safety of my loved ones once they leave home.

It is the work of people like yourselves that makes all the difference in the world. When I and my staff



visit these trauma centers, it is exceedingly clear that what you do keeps our loved ones safe.

I urge you to rise to the challenge. Expand the approach to crash avoidance and post crash protection, recognize the "living link" of expanded dialog, and

let's create the tools and resources needed to support these changes. Together we can build a bridge to the 21<sup>st</sup> century that ensures safe passage for generations to come. Thank you very much.

## **The Honorable David M. Collenette**

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Minister of Transport  
Canada

Good morning, ladies and gentlemen.

It gives me great pleasure to be here at the 16th Enhanced Safety of Vehicles Conference today. I'd like to begin by welcoming everyone to Canada and, more specifically, to Windsor. I hope you will have time to visit the area before you leave to return home.

We at Transport Canada consider the ESV conferences an invaluable opportunity for researchers and for industry and government representatives to share recent advances in motor vehicle safety technology. By promoting co-operation in research and the international harmonization of safety regulations, conferences like these play a major role in improving the safety of road transportation in Canada and indeed throughout the world. That's important for everyone.

In Canada, we have witnessed a 50 per cent decline in traffic fatalities over the past 25 years, even though traffic has doubled. The figures for 1997 are the lowest since these statistics began to be compiled.

But even one fatality is one too many. We — and by "we" I mean the federal and the provincial and territorial governments — are committed to making Canadian roads the safest in the world. Statistics from the Organization for Economic Cooperation and Development indicate that Canada now ranks seventh in terms of fatalities. We will continue to work on improving our record and will be looking to other countries to see what initiatives have worked best for them.

### **Safety is Everyone's Concern**

My departmental officials have implemented a wide range of activities to bring us closer to our goal. After all, regulation and infrastructure improvements can only do so much. Public awareness and public commitment are also critical to road safety.

That's why we're working with government and industry partners through the National Occupant Restraint Program to increase the use of safety restraints in vehicles, for example. Our goal is for 95 per cent of occupants of light-duty vehicles to

consistently buckle up by the year 2001.

We have already seen positive results — much of the recent improvement in road safety can be attributed to increased seat belt use, which is currently at 92 per cent for Canadian drivers. We are quite proud of this statistic, which is among the best in the world. It is the direct result of collaborative work on improved seat belt design, seat belt and child restraint legislation, police enforcement programs and public education efforts.

Similarly, our Strategy to Reduce Impaired Driving aims to reduce injuries related to drinking and driving by 20 per cent, also by the year 2001.

The need for improved communication about safety issues is underscored by a recent survey. Despite the fact that road fatalities are down 15 per cent, nearly half of Canadians polled believed that the safety of our roads had declined over the last five years.

We're working closely with our partners to improve the public's confidence in the safety of our road transportation system.

### **Protecting Our Children**

We are currently focusing our efforts on children. A recent survey gives cause for concern — at least 25 per cent of children on Canadian roads are either not properly restrained in child seats, or are in seats that are inappropriate for their size and weight. In most cases, the parents thought they were securing their children safely. Clearly, there is a need to provide the public with more information about the proper use of child restraints.

To address this need, I have requested the development of a national public awareness campaign — targeted at parents and other caregivers — to increase awareness of the dangers of improper use of these devices.

Transport Canada staff are developing promotional materials such as videos, brochures, and pamphlets, which will be available later this year. The department is also working on improving safety regulations to

ensure that manufacturers make child restraints that are easy to use properly.

To make our regulations as effective as possible, Transport Canada — with the Children's Hospital of Eastern Ontario (CHEO)— is planning a two-pronged multi-disciplinary study of children involved in real-world motor vehicle crashes.

The first component is a study, based in the national capital region, of all children who are admitted to CHEO as a result of a motor vehicle collision. The second takes the national perspective and will involve several hospital and university-based collision investigation teams. This study will focus on children who sustain injuries from seat belts or air bags.

The objective of these studies is to collect detailed information about the nature and severity of motor vehicle collisions involving children, and the injuries that result. We believe that the combination of the automotive safety engineering expertise of Transport Canada and the medical knowledge of the participating physicians will help the industry to produce better occupant restraint designs. It will also serve to help target public awareness campaigns that promote proper child restraint use.

Transport Canada is working hard to improve the safety of motor vehicles generally.

### **Fine-Tuning the Equipment**

Out of concern about injuries caused by air bags, we recently conferred with the provinces and territories, with the U.S. National Highway Traffic Safety Administration (NHTSA), and with vehicle manufacturers and dealers to develop an air bag deactivation program for the rare cases where deactivation might be warranted. The program is now in place, and explanatory brochures and application forms are available for anyone considering such action.

This is not to say that air bags are unsafe. Quite the contrary. I want to emphasize that air bags provide an additional level of safety beyond seat belts. It has been estimated that air bags have saved nearly 150 lives since their introduction in Canadian vehicles in the early 1990s.

Moreover, we are pleased to note that vehicle manufacturers have responded to concerns with the introduction of second-generation air bag systems that deploy at lower speeds, thereby reducing the risk of injury. Most 1998 models sold in Canada have these second-generation air bags.

And Transport Canada researchers are currently working with NHTSA to develop even more advanced air bags — a third generation if you will — which deploy according to variable parameters, depending on

occupant characteristics and collision circumstances.

Side-impact protection is another area of vehicle design that we believe can save lives. We've launched a major research program to study real side-impact collisions and to conduct crash tests, in order to develop new, dynamic requirements for side-impact protection. We are working closely with our colleagues in the U.S., the European Union, Japan and other countries to develop the first internationally accepted side-impact test dummy. This is important in today's world of international manufacturing and global markets.

### **International Harmonization**

To further contribute to international research in road safety, Canada has also been participating in international harmonized research working groups under the auspices of ESV. This is important research, and we intend to continue our participation for some time to come.

And we are working through NAFTA, APEC and the United Nations Economic Commission for Europe to promote the international harmonization of motor vehicle standards to improve road safety all over the world.

Which isn't to say that we're trying to make everyone conform to the same detailed regulations. Every country must take responsibility for safety in its own jurisdiction and will, of course, reserve the right to set unique standards and regulations to meet the requirements of its own citizens. A good example of this is Transport Canada's 1990 regulation requiring daytime running lights in Canada — a move that resulted in about a 10 per cent reduction in collisions.

My department is currently revising the Motor Vehicle Transport Act, which regulates the safe operation of trucks and buses in Canada. We are aiming to improve not only road safety, but also the competitiveness of the Canadian motor carrier industry with our amendments. I hope to table this Bill in the House of Commons later this year.

### **Technology**

Technology plays a major role in transportation today and must be part of any plan to improve our systems.

Wide-spread recognition of the potential benefits of Intelligent Transportation Systems (ITS) to the efficiency of the Canadian transportation system have resulted in millions of dollars in investments towards the development of such improvements as route guidance systems, collision avoidance systems and

heads-up displays.

Still, this new technology will have to be proven safe before it can be used. Safety has always been — and will always be — Transport Canada's top priority, and we have been working closely with other countries through the IHRA [International Harmonized Research Activities] to develop methods of assessing the human factors involved in using this technology.

Which brings me to the theme of this year's conference — the need to take the human factor into consideration in developing new safety technology.

This is of critical importance. Research demonstrates that human factors are responsible for some 90 per cent of motor-vehicle collisions.

We must make new safety technology user-friendly, as well as efficient, so that people will use it — and use it right. We will not sacrifice safety for efficiency.

But there is another safety issue I'd like to mention here—that's technology-related.

#### **Year 2000 Issues**

As we approach the year 2000, we have more to look forward to than a giant birthday party. The turn of the century also poses what could be a huge technological challenge, in the form of the so-called "millennium bug."

Computers all over the world, including those that control transportation manufacturing and systems, could be affected.

As the department responsible for regulating transportation safety in Canada, we are encouraging industry to become more aware of the problem and its implications for transportation safety. We recognize

the potential for problems related to this computer glitch and have created a working group to systematically examine attendant safety concerns.

While we are confident that industry will find effective solutions, we will nonetheless monitor the steps the various federally regulated transportation modes are taking to address the issues.

We will assess industry's progress in dealing with all potential problems well in advance. We have adequate regulatory authority under existing legislation to take action if concerns about safety continue — and we can and will respond promptly if necessary.

#### **Meeting the Safety Challenge**

Ladies and gentlemen, I've outlined the challenges we are facing with regard to road transportation safety and delineated some of the steps we in Canada have taken to meet those challenges.

While there's no such thing as absolute safety in transportation, we intend to get as close to that as technology and hard work will allow. And we're doing well. Despite the impression sometimes left by the news media with their focus on accidents, Canada has an enviable safety record.

A record like ours doesn't just happen. It results from a commitment to safety on the part of all the players — a commitment that is backed by effective federal regulation and enforcement of national standards.

My hope is that by pooling our knowledge at conferences like these we can make a positive difference in the safety of transportation the world over.

Ladies and gentlemen, thank you.

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# U.S. Government Awards Presentations

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Presenter: Ricardo Martinez, M.D., Administrator  
National Highway Traffic Safety Administration, United States

## U.S. Government Awards for Safety Engineering Excellence

In recognition of and appreciation for extraordinary scientific contributions in the field of motor vehicle safety engineering and for distinguished service to the motoring public.

### Canada

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**Eric R. Welbourne**  
Transport Canada

Mr. Welbourne has demonstrated exceptional leadership in the research field of human biomechanics and vehicle crashworthiness in support of motor vehicle safety regulations. His work has advanced fundamental understanding of human response in vehicle crashes. In particular, his modeling work has contributed to the advancement of scientific

knowledge concerning the biomechanics of injury involving the head, chest, and lower extremities. As a result of this research, important changes to Transport Canada's occupant protection policies and vehicle safety regulations have been made. For these contributions to automotive safety, he is being recognized with this award.

### France

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**Jean-Yves Le Coz**  
PSA Peugeot/Citroen/Renault

Dr. Le Coz has dedicated his professional life to obtaining greater knowledge in the field of road safety. Leading collaborative laboratory efforts with vehicle manufacturers has resulted in the development of passive safety and collision avoidance technology

responsible for the development of safer vehicles. His professionalism and competency in providing the scientific population with laboratory accidentology and biomechanics research knowledge is deserving of this special recognition.

### Germany

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**Klaus Oehm**  
Volkswagen

Mr. Oehm has worked in the field of motor vehicle safety research for over 25 years. Mr. Oehm played a leading role in the development of the first passive restraint system to go into series production. In 1996 Volkswagen introduced in the *Golf*, a seat-integrated side airbag system for front seat occupants. The *Golf* became the first car in its class to be offered with this

occupant protection system. Mr. Oehm was among those primarily responsible for the development of these systems. Many members of the motoring public have been protected in a variety of crashes world wide through the outstanding efforts of Mr. Klaus Oehm. For these contributions to international automotive safety, he is being recognized with this award.

## Japan

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### **Tetsuo Tsuchida**

Honda R&D Company

Mr. Tsuchida is being recognized for his contributions in enhancing the safety of motorcycles. He was responsible for the development of a combined front-rear anti-lock braking system which lead to improved operation of motorcycles and greatly contributed to rider injury prevention. This improved

safety technology was applied to mass production for large motorcycles and small scooters. For his contributions of improved safety operation of two wheeled vehicle brake systems, Mr. Tsuchida is being recognized.

## Sweden

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### **Ingrid Skogsmo**

Volvo Car Corporation

Mrs. Skogsmo has been instrumental in the development of several new and unique test methods and injury assessment criteria. Under her leadership at the Volvo Safety Center, the department has successfully developed criteria and provided research in the development of Volvo's most recent safety innovation, the Inflatable Curtain and the Whiplash

Protection Study. Her work with side impact methodology and criteria has been implemented in the well known Side Impact Protection System, SIPS, and in 1994, the development of the side impact airbag, SIPS-Bag. For her contributions to motor vehicle safety worldwide, Mrs. Skogsmo is deserving of this special recognition.

## United States

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### **John W. Melvin**

General Motors Corporation

Dr. Melvin has devoted over 30 years of his career to improving motor vehicle safety. He is being recognized for his significant contributions to automotive safety through his unique capability to apply knowledge in biomechanics to enhance safety design. His research in biomechanics has helped to improve the design of airbags, belt restraints, seats, and

interiors in today's passenger cars. His pioneering work in demonstrating how protection can be enhanced in high energy crashes on race tracks has helped lay the groundwork to extend that knowledge to passenger car protection. Dr. Melvin is deserving of this special recognition.

## U.S. Government Special Awards of Appreciation

In recognition of and appreciation for outstanding leadership and extraordinary contributions  
in the field of motor vehicle safety.

### Poland

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**Wojciech Przybylski**  
Motor Transport Institute

Mr. Przybylski is being recognized for his leadership and vision to promote motor vehicle safety in Poland. He is also being recognized for his efforts in international cooperation for motor vehicle safety regulations. He has forged a closer connection for Poland and motor vehicle researchers in different

countries through his entry into the ESV Technical Conference and active participation in the International Harmonized Research Activities. For his dedication and commitment to enhancing motor vehicle safety worldwide, Mr. Przybylski is being recognized with this award.

### Sweden

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**Lennart Johansson**  
Volvo Car Corporation

With an expansive career in motor vehicle crashworthiness research and development, Mr. Johansson is a leader in improving motor vehicle safety. His unique ability of understanding the urgent need to develop and introduce new restraint systems for the

occupant's best protection, and his leadership to get the best performance restraint systems on the market as early as possible has contributed to motor vehicle safety worldwide. For these contributions, Mr. Johansson is being recognized with this award.

### United Kingdom

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**C. Adrian Hobbs**  
Transport Research Laboratory

Mr. Hobbs' research on the behavior of car structure in frontal impacts, and their influence on injuries to occupants, lead to the development of the European Enhanced Vehicle Committee's (EEVC) Offset Deformable Front Impact test procedure. Mr. Hobbs has been involved in motor vehicle safety

research since 1972, and is now one of the leading experts in understanding the structural behavior of cars in crashes. For this and his numerous contributions to improving motor vehicle safety, Mr. Hobbs is being recognized with this award.

### United States

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**H. George Johannessen**  
OmniSafe, Incorporated

Mr. Johannessen has contributed more than thirty years of dedicated service in advancement of vehicle occupant safety through professional engineering efforts and public education. Mr. Johannessen has served on numerous national and international

automotive safety-related committees and has demonstrated outstanding leadership to further the understanding of motor vehicle safety. Mr. Johannessen is deserving of this special recognition.

## **United States**

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### **Richard F. Humphrey**

General Motors Corporation

Mr. Humphrey is being recognized for his unique and extraordinary contributions to promote the cause of safety through highly effective communications in motor vehicle safety matters. Mr. Humphrey is an active participant on various committees, and works with numerous transportation related activities to promote understanding of issues and to achieve

solutions beneficial to the motoring public. He is an accessible technical expert, a coalition builder, and an influential advocate for improving motor vehicle safety. For his service and dedication to the safety of the motoring public, Mr. Humphrey deserves special recognition.



## **U.S. Government Special Recognition Presentations**

### **ESV Distinguished Service Award**

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#### **Linda L. O'Connor**

National Highway Traffic Safety Administration (Retired)  
United States

In recognition of and appreciation for your distinguished service. The United States Department of Transportation, National Highway Traffic Safety Administration, our International Partners, (Germany, France, Italy, Japan, The Netherlands, The European Commission, United Kingdom, Sweden, Canada, Belgium, Australia, Hungary, and Poland) and the

motoring public present you with this award. Your involvement in coordinating, organizing, and providing the ultimate leadership at the International Technical Conference on the Enhanced Safety of Vehicles (ESV) as ESV Technical Coordinator is an extraordinary achievement.

### **ESV Appreciation Award**

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#### **Vittoria Battista**

Transport Canada  
Canada

On behalf of the U.S. Department of Transportation, it is my pleasure to recognize you for your outstanding achievements as the Program Manager, for the 16<sup>th</sup> International Technical Conference on the Enhanced Safety of Vehicles, May 31 to June 4, 1998, Windsor, Ontario, Canada.

The National Highway Traffic Safety Administration is grateful for your work and commitment to motor vehicle safety research. Your talents and organizational skills served to facilitate the international exchange of technical information.

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# Government Status Reports

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Chairperson: Jean-Pierre Médevielle, INRETS, France

## Commission of the European Community

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**Herbert Henssler**  
European Commission

### Abstract

This paper reviews the activities of the European Community in relation to the EC Type-Approval legislation for motor vehicles and its safety-related requirements which occurred since the last ESV-Conference.

The importance of the accession of the EC to the 1958 Agreement of the UN/ECE motor vehicle regulations is emphasised and its effects on the regulatory activities are explained

The new directives on the protection of car occupants in front and side impacts are presented as well as the intended legislation on the protection of pedestrians in the event of collision with cars. Furthermore, the paper outlines the current activities aiming at enhanced safety of buses and coaches, child restraints and frontal protection for trucks. The paper also gives an overview on safety related research projects, which are promoted by the EC in the framework of its R & D programme.

### Introduction

Mr. Chairman, I wish to thank you on behalf of the European Commission for the invitation to present again the report on the regulatory activities of the European Community in the automobile safety sector. Many important developments have occurred in the EC since the last ESV Conference in Melbourne two years ago, and I am pleased to report on these here at this outstanding forum. The activities of the EC cover, of course, all the important aspects of road safety: traffic regulations, driver related regulations and regulations relating to the vehicle construction. As the competence of the department I am representing is limited to the latter aspect, I will focus my presentation on the developments in the area of vehicle safety.

### The Accession to the Revised 1958 Agreement of the UN Economic Commission for Europe

The most important development which took place

in the interval considered has been the accession of the EC to the Revised 1958 Agreement of the UN/ECE on 24 March 1998. The internal process of the EC on which I had reported at the previous Conference has been achieved on 29 November 1997 by a decision of the Council of Ministers with the assent of the European Parliament.

The decision to accede to the Agreement is of paramount importance for the evolution of the automobile regulations of the EC. On the one hand the ECE regulations to which the EC adheres -78 so far- will be directly applicable and give access to the internal market of the EC. Where of interest to the EC, ECE Regulations could quite simply be carried over into the EC Type-Approval system and thus be made mandatory on its internal market. On the other hand, as a Contracting Party to the Agreement the EC can now actively participate, in accordance with its economic importance, in the process of establishing technical regulations in this international forum which has, among other things, a high reputation as the key international regulatory body in the area of vehicle safety. In this context the Commission welcomes the recent news from Tokyo on the approval by the Diet of Japan's accession to this Agreement.

In the interest of transforming the ECE in Geneva into a truly global forum, embracing also Canada and the US, Commission representatives have actively cooperated with the American and Japanese experts to establish a tri-partie proposal for a complementary agreement which has been submitted to the Working Party 29 of the ECE at its March session of this year. At its forthcoming June session, comments of this proposal which are introduced by other interested parties will be discussed. It is the intention to open this agreement for signature as soon as possible.

### EC Type-Approval

As reported at the previous Conference, the EC type-approval became mandatory, on 1 January 1996, for all vehicles of the international category M1: that is passenger cars and similar vehicles such as motor



caravans. From 1 January 1998, each car sold and registered in the EC must have an EC Whole Vehicle Type-Approval unless it is built individually or produced in small series. In relation to this latter obligation, the EC Type-Approval procedure has been reviewed early this year in order to make its administrative aspects more practicable and expedient. The work in order to extend the provisions of the EC Type-Approval to all other vehicle categories is making good progress and a decision is expected in the near future.

The accession to the 1958 Agreement will also require adequate amendments of the EC Type-Approval in view of the direct applicability of ECE-Regulations within this procedure. This work has recently been started.

Whilst the initial and fundamental objective of EC Type-Approval has been a commercial one, i.e. to achieve the internal market of the EC in the vehicle sector, the current provisions of the Treaty of the EC on which this procedure and its technical requirements are based, require that a high level of safety, environment and consumer protection must be assured by such regulatory initiatives.

Hence, the EC Type-Approval constitutes the ideal basis to introduce, for the whole of the EC, stringent requirements relating to the construction of vehicles, vehicle systems and components which affect safety and environmental protection. Another consequence of this fundamental requirement is that the Commission has to carefully monitor the progress of the automotive technology in order to adapt the technical requirements of the EC Type-Approval to the state of the art whenever appropriate.

Equally, the increasing public pressure for improved road safety and environmental protection is a motivation for the Commission to amend existing directives or to establish proposals for new directives. Here again, the accession to the 1958 Agreement will make this task of the EC easier as full use of the expertise of the ECE working groups will in the future be possible.

In the following I will elaborate essentially on the progress made on regulations relating to the safety of vehicle occupants and pedestrians, issues where we have identified considerable need for improving the present situation.

### **Protection of Occupants in Front and Side Impacts**

The 2 directives which were under discussion at the time of the Melbourne Conference have been adopted by the Council and the Parliament of the EC in

May 1996 and December 1996 respectively (directives 96/27/EC and 96/79/EC).

The directives reflect the most recent state of the art, both as far as the representative with respect to real-world accidents in the EC and the biomechanical aspects are concerned. The rationale for and the contents of these directives have been explained at the previous Conferences. It is simply recalled that Directive 96/79/EC on front impact protection specifies a test of the vehicle to be approved against a fixed, offset, deformable barrier at 56 km/h. The biomechanical criteria for assessing the protective characteristics of the vehicle relate to the head, neck, thorax, femur and lower leg.

The Directive 96/27/EC on lateral impact protection relies on a test with a mobile deformable barrier against the stationary vehicle at 50 km/h. The biomechanical protection criteria relate to the head, thorax and pelvis.

As initially proposed, both Directives become mandatory, for new types of cars, from 1 October 1998, and for all new cars entering the market and registered in the EC from 1 October 2003 onwards.

When Council and Parliament adopted these directives they gave precise instructions to the Commission concerning the review of certain details at short term and the further evolution of their specifications at longer term. The work concerned has been entrusted to the European Enhanced Vehicle-Safety Committee (EEVC) which will report on this in more detail in their status report

### **Protection of Pedestrians and Other Vulnerable Road Users**

Legislative measures aiming to ensure that car fronts are as "pedestrian friendly" as possible are under discussion in Europe since several years and continue to figure on the work programme of the Commission.

In view of the considerable differences in the evaluation of the cost of such measures in relation to their benefits, the Commission has entrusted a renowned institute with a comparative study of the available cost/benefit assessments in order to get a conclusive opinion on this aspect. The results of this study have been presented in January 1998 to a meeting of experts from the national administrations, industry and consumer organizations. At the end of this meeting, the majority of the consulted experts were affirmative both as regards the need and the technical feasibility of the intended measures.

In the meantime, EEVC which, 4 years ago, had developed the test methods and protective criteria which are the basis for this directive, has accepted to review the specifications concerned in order to take account of the most recent accident studies.

On this basis, the Commission will be in a position to finalize its proposal for a comprehensive, performance-related directive and submit it to decision makers of the EC for adoption.

### **Safety of Buses and Coaches**

The safety of persons transported in buses and coaches remains a priority area of the regulatory programme of the EC.

The proposal for construction requirements for buses and coaches which has been announced at the Melbourne Conference, has been presented to the European Council and Parliament in October 1997.

Once adopted, this directive will set specifications for rollover strength and stability, stipulate the number and dimensions of exits for normal use and for use in emergency evacuation, and establish minimum dimensions for seats and gangways. Administratively, the directive will allow for the type-approval of buses and coaches as complete vehicles and, for the benefit of specialized bus body manufacturers, also of the bodywork as separate technical units.

As far as the above mentioned requirements are concerned the directive follows the corresponding regulations of the UN/ECE. A specific feature which the EC Commission has added to its proposal are mandatory requirements relating to the accessibility of buses and coaches for persons with reduced mobility.

The discussions of this proposal in the Parliament and Council are underway and it is hoped that the final adoption by these institutions will occur before the end of this year so that the intended implementation date of 1 October 1999 can be respected.

In the meantime, the Commission has amended, by means of the procedure of adaptation to technical progress, three existing directives relating to seat belts, seat belt anchorages and the strength of seats in order to introduce the mandatory fitment of seat belts, and in some cases energy absorbing seats, in all seating positions of medium and large buses and coaches. The directives specify the fitting of 3-point belts in minibuses, where the risk of injury in frontal impacts is high, and 2-point belts and energy-absorbing seats in large coaches, where the main risk of injury relates to ejection during roll-over.

These measures entered into force on 1 October 1997 for new types of buses and coaches and will become mandatory on 1 October 1999 for any new

such vehicle sold and registered in the EC. (For minibuses with a total mass of less than 3.5 tons the implementation dates are October 1999 and October 2001.)

In order to acquire the necessary technical background for further improving the safety of occupants of buses and coaches, the Commission has entrusted a European consortium with a comprehensive study of state-of-the-art test procedures and requirements for restraint systems specifically conceived for such vehicles. The results of the study will be presented at this Conference.

### **Child Restraints**

Taking account of the public interest of enhancing the safety of small children transported in passenger cars, the Commission has introduced this issue into its regulatory work programme.

With its accession to the 1958 Agreement the EC has adhered to the Regulation 44 of the ECE relating to safety of the construction of child restraints. This regulation represents the relevant state of the art and is already widely applied in Europe. The Commission intends, therefore, to add the reference to the technical specifications of this regulation, together with appropriate installation requirements, to the existing directive 78/541/EC relating to safety belts and restraint systems, currently limited to specifications for such systems for adult occupants.

This process will be carried out by the Commission in the framework of adaptation of the existing directive to technical progress and is expected to be achieved before the end of this year.

### **Front Underrun Protection for Heavy Commercial Vehicles**

Public concern in Europe about frontal collisions between trucks and cars where the latter underrun the front structure of the truck is increasing and has induced the Commission to add this issue to its regulatory work programme.

Here again the EC has adhered with its accession to the 1958 Agreement to an existing ECE Regulation (n° 93) which specifies a static test procedure for front protective devices for heavy commercial vehicles. The devices resulting from the application of this regulation have proven to be a cost-effective way to reduce the consequences of a frontal collision with a truck for the occupants of a passenger car. The Commission therefore intends to propose to the European Parliament and Council to adopt a new separate directive in order to introduce the technical

requirements of the Regulation 93 into the EC Type-Approval system. This proposal is expected to be ready in the course of 1998.

### **Support to Research Projects**

In order to contribute, in general, to the efforts to reduce the number of fatalities caused by road accidents and, in particular, to establish a scientific basis for the evolution of the European legislation in the field of passive safety, the EC Commission sponsors a considerable number of relevant research projects through its R&D budget.

The current R&D programme focuses on the question of vehicle compatibility in different accident modes, the improvement of the representativity of the test procedures relating to frontal and lateral impacts including the development of advanced anthropomorphic dummies and the different aspects of pedestrian protection.

The partners of the Commission are, as already mentioned, the EEVC, other research institutions and universities and also the European automotive industry and its suppliers interested in passive safety.

For the next R&D programme it is proposed to establish a European network on passive safety in order to link together and coordinate the different projects funded by the EC and its Member States.

It is intended, where it is of interest, to establish a relationship between this network and the International Harmonized Research Activities (IHRA) process in view of establishing a world-wide research basis for future regulatory initiatives.

I have noted that in the technical sessions of the Conference, different papers will refer in more detail to these research projects.

### **Conclusions**

Subject to the conclusion of the work on pedestrian protection the EC Type-Approval procedure

and its technical requirements are in principle completed for passenger cars. The next future will see the Commission to focus its activities on the extension of this procedure to the other categories of road vehicles. This will, in the area of vehicle safety, require a few new directives and the appropriate amendment of the technical requirements of a number of existing Directives. The work to this aim is under way and I hope that substantial progress can be reported at the next ESV-Conference.

The accession to the Revised 1958 Agreement will of course affect the future regulatory process of the EC, as it offers now the possibility to develop technical regulations affecting the design and construction of motor vehicles in the future on a wider international basis.

We welcome in this respect Japan's decision to adhere also to the Agreement, and that Australia has taken steps to start the internal process in view of its accession. We hope that other important motor vehicle producing countries in the world which are not currently Contracting Parties will follow and also join this Agreement in the interest of free global trade unimpeded by technical obstacles.

We are also supportive of the initiative of the United States to create a complementary agreement aiming at the establishing of global technical regulations as this would eventually establish the basis for an effective world-wide harmonisation in the automobile sector.

This achievement would not only be beneficial to our industries but also to their customers in the whole world who would be able to acquire motor vehicles offering a high standard of safety and environmental protection at reasonable cost. I consider this conference as being an excellent contribution to this objective.

I thank you for your attention and wish the Conference and its organisers a great success.

## Federal Republic of Germany

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**K.-H. Lenz**

Bundesanstalt für Straßenwesen

It is an honour for me to present the status report of the German Government at the 16<sup>th</sup> ESV Conference again this year.

### Road Construction and Traffic Engineering

As already mentioned at the last ESV Conference, approximately 47 % of the total distance travelled by motor vehicles is accomplished on federal trunk roads. The concentration of motor vehicle traffic on the federal autobahns is particularly high. Approximately 30 % of the vehicle kilometrage is completed on autobahns even though they constitute only approximately 1.8 % of the total road network length.

In 1993, on the basis of the 1992 Federal Traffic Infrastructure Programme, the German parliament passed the 4<sup>th</sup> Act Amending the Improvement of Trunk Roads Act with a requirement plan for the expansion of the federal trunk roads which provides for an investment volume of approximately 210,000 million DM by the year 2012 for urgent projects for improving and enlarging the road network.

The increase in the efficiency of the roads which results from increasing their width to six or eight lanes increases the capacity and improves the quality of traffic flow and operation. The present total length of autobahns with six or more lanes in the federal autobahn network is 1698 km including constructions completed in 1996 (approx. 15 % of the network). Federal autobahn expansion is focused primarily on the roads being improved as part of the "German Reunification" traffic project and on the main through-traffic autobahns A1-A9 which are subject to heavy loads; these are the European roads, which run through Germany from one national border to another. Extensive investments continue to be made, above all in the autobahns in the new federal Laender and particularly in measures for increasing traffic safety, (reconstruction of one-way

roadways, construction of hard shoulders for emergency parking, repair of bridges).

On the federal highways, accident black spots (e.g. curves or hill-crests with overly small radii, junctions and intersections with poor sight distances) are being redesigned step by step. Under the programme for the construction of bypasses, to which approx. 30 % of the funds provided for expansion of the federal trunk road network have been allocated since 1978, it was possible to open 40 bypasses (total length 109.5 km) for traffic in 1996. In total, 1,178 million DM were spent on the construction of bypasses in 1996 alone (1994: 1,076.6 million DM).

In 1996, approximately 54.8 million DM were available from the road construction plan for the elimination of at-grade railway crossings on federal highways as well as for other technical safety measures. These measures were continued in 1997 as well.

Work sites on the federal autobahns are required for maintenance and improvement of the roads (40 % of the federal autobahns in the old Laender are more than 20 years old). In 1996 and 1997 respectively, approximately 700 work sites were present for longer periods (more than 14 days on federal autobahns). The Federal Government co-ordinates such long-term construction measures with the Laender within the scope of the construction planning. The revised "Codes of practice for construction planning on federal autobahns" were introduced in 1996 as a supplement to the "Codes of practice for the safety of work sites on roads" to improve work site management on autobahns. The focal points of this new edition include the avoidance of too many work sites in any particular area of the road network, a new work-site information sign and introduction of a traffic congestion evaluation process. A system providing drivers with information on work-sites on federal autobahns was integrated into the Federal Ministry of Transport's Internet site in 1997. The information on long-term work sites is updated each week.

Traffic-actuated traffic management systems are used to adapt driving speeds to the particular traffic and weather conditions and close lanes for traffic as required. The Federal Ministry of Transport has extended the programme for traffic management systems on autobahns for the period 1996 - 2001 to enlarge the application area of such systems. The length of autobahn sections provided with such systems was approx. 550 km at the end of 1997. By the end of 2001 the length is to be expanded to 1,100 km. Diversion recommendations can be indicated using variable direction signs over a length of approximately 1,400 km of autobahns. By the end of 2001 an additional 700 km are to be equipped with such signs. In 1996 and 1997 the Federal Ministry of Transport allotted a total of approximately 150 million DM to the Laender for the installation of such systems.

Situation-actuated traffic management systems are being installed to an increasing extent on federal highways to make accident black spots less dangerous. The Federal Ministry of Transport invested 13.3 million DM for 17 systems during the report period of 1996 - 1997 which meant that, at the end of 1997, 174 such systems with a total value of approx. 51 million DM were in operation improving traffic safety on federal highways. These include the following types:

- Traffic-actuated traffic signal systems for the improvement of safety at junctions.
- Systems at selected points for traffic or weather-actuated warnings of accident black spots.
- Systems for traffic management with traffic or weather independent control of the traffic at critical road sections.
- Systems for network management for bypassing congested areas.

Since the sixties, passive protective devices (vehicle restraint systems) on roads such as crash barriers, protective concrete walls and impact-reducing casings for crash barriers have served to protect vehicle occupants

during road traffic accidents. The guideline upon which the installation of such equipment is based is at present being revised with regard to the future European standards. Crash tests prove that the existing passive protective equipment in Germany has a relatively high safety standard which helps to keep damage resulting from accidents low. Impact-reducing casings for crash barriers improve the safety for motorcyclists and moped riders still further at critical road sections (e.g. in curves).

The Federal Ministry of Transport introduced the revised "Codes of Practice for the Design of Roads, Section on Cross-Sections - RAS-Q 1996 Edition" during the reporting period of 1996 to 1997. There are new developments in this area with regard to cross-sections on autobahns as well as on federal highways. These codes of practice include for the first time a procedure for the specific consideration of traffic safety aspects when several cross-sections are possible options from the point of view of traffic engineering.

Between 1996 and 1997, technical terms of delivery were elaborated for work site safety elements (e.g. traffic barriers, temporary markings and installation devices). The technical requirements relating to the materials and corresponding provisions are included in these terms.

The "Recommendations for Bicycle Traffic Systems - ERA, 1995 Edition" revised by the Road and Traffic Research Association (FGSV) deal mainly with the safe design and operation of bicycle traffic systems. They are harmonised with the new road traffic regulations and the administrative regulations on bicycle traffic.

Responsible motor vehicle drivers are able to assess the majority of road condition characteristics (e.g. slippery due to snow, danger of aquaplaning during heavy rain). However, this does not apply in the case of skid resistance. While the contribution of the roadway to skid resistance remains virtually constant, tyre developments have to be re-evaluated. The technical road construction specifications have been documented in the

"Guidelines Concerning Skid Resistance and Traffic Safety on Wet Roads" by the FGSV in cooperation with the Federal Ministry of Transport. These guidelines are at present being updated. In 1996 the regular recording of the condition of the federal trunk roads was introduced through a General Circular from the Federal Ministry of Transport. In the future safety-relevant characteristics of the condition of the roads such as ruts and skid resistance will be regularly recorded. Damaged points will be recognised and eliminated in time through specific measures.

### European Integration and Road Traffic Regulations

The efforts of individual countries to harmonise their national regulations in connection with European integration are based on the Maastricht Treaty. In Article 75 Paragraph 1 letter c) of the EC Treaty, the European Community is assigned the responsibility for traffic safety, although the so-called "subsidiarity principle" applies. Article 3 b of the agreement states in this regard: "In areas for which it is not solely competent the community shall, in accordance with the subsidiarity principle, take action only in as far as the objectives of the measures in consideration cannot be achieved to a sufficient degree at Member State level and therefore can, due to their scope or their effect, be better achieved at Community level".

In this context the German Federal Government is of the opinion that all questions regarding behavioural regulations in road traffic can be better and more effectively regulated at a national level than by central regulations which should apply in all Member States but which cannot take into consideration the differences in mentality of the citizens of the individual EU member countries. Rules governing behaviour can be effective when they are linked to the attitudes and patterns of behaviour of those affected; these have developed differently in the various regions of Europe.

At its convention in June 1997 the EC Council of Transport Ministers favourably acknowledged the

recommendation of the European Union (EU) to promote traffic safety in the EU (programme 1997 to 2001). The primary objective of this programme is the further reduction of personal injury road accidents in Europe from approx. 45,000 fatalities at present to 25,000 in the year 2010. Public and private measures are to be initiated for this purpose. The following focal points of action are described in the programme:

- further development of the CARE traffic accident data base
- development of an information system on traffic safety measures
- technical and telematic applications for the support of motorised road users
- measures against overfatigue and driving under the influence of alcohol, medication and drugs.

In an ordinance amending road traffic legislation which came into force on 1<sup>st</sup> September 1997, the Road Traffic Regulations were changed particularly with a view to improving the safety of bicycle traffic (bicycle amendment) and therefore also of promoting the bicycle as an environmentally sound means of transport. In the interest of the safety of child bicyclists, for example, the age limit for riding bicycles on footways was increased from up to 8 years to up to 10 years. Under the Road Traffic Regulations children of up to 10 years of age can now ride their bicycles on footways even when cycleways are present. The previous obligation to use bicycle paths no longer applies to this age group as newer forms - such as cycle lanes- are too dangerous for them. Bicycle roads, to which motor vehicle traffic has access only under certain circumstances, were also included in the Road Traffic Regulations; special bus lanes can be opened for bicycle traffic. The new protective strips are also intended to offer cyclists greater safety. The opening of certain one-way streets for bicycle traffic travelling in the opposite direction, introduced as

a test by order of the Bundesrat, also serves to promote bicycle traffic.

Moreover, the regulations for the use of traffic signs and equipment have been made more exact. The traffic sign density in the Federal Republic of Germany is one of the highest. An excessive number of signs in traffic leads to a general overtaking and distraction of road users. In order to avoid this in the future, rulings have been drawn up in the Road Traffic Regulations and the associated administrative regulations with the objective of using as few traffic signs as possible and as many as necessary. The target is to remove "unnecessary" traffic signs along public roads.

According to criminal law provisions §§ 315 c and 316 of the Criminal Code, any person who drives a motor vehicle although not in a position to do this in a safe manner as a result of the consumption of alcoholic beverages or other "intoxicating substances" shall be liable to punishment. In contrast to alcohol, there are as yet no threshold values in the case of drugs for assuming absolute driver incapacity. A conviction for driving under the influence of drugs is possible only when driver incapacity can be definitely established and proved. It is frequently difficult to ascertain relative driver incapacity. A regulatory offence similar to the 80mg / 100ml alcohol concentration in blood, which applies regardless of whether driver incapacity has been established, does not exist to date. The Federal Government has closed this loophole in a draft law. Under this draft law, driving a motor vehicle under the influence of certain drugs will be punished as a regulatory offence with a fine and driving ban.

Since 1<sup>st</sup> July 1991 drivers of certain vehicles for the transport of dangerous goods must participate in special training. This training must be repeated every 3 years. Since 1<sup>st</sup> January 1997 the same training and testing principles apply in the countries prescribing to the European Agreement Concerning the International Carriage of Dangerous Goods by Road. This standardisation was brought about due to a German

initiative and takes into account the courses of training developed in Germany. It is now obligatory for vehicle drivers in all participating countries to prove the knowledge thus obtained by successfully passing a test. Decreasing accident figures for vehicles carrying dangerous goods indicate that such training has been a success.

Since 1<sup>st</sup> October 1991 it has been obligatory to appoint dangerous goods advisors in all transport companies which deal with the carriage of dangerous goods. They supervise observation of the regulations governing the transport of dangerous goods in their companies. Within the scope of training programmes they obtain the required knowledge of their obligations and the safety aspects of international regulations for the transport of dangerous goods. This safety concept has led to a decrease in the number of accidents in the carriage of dangerous goods resulting from failure to observe the safety regulations.

The positive experiences in Germany have led to a comparable regulation being passed for the territory of the European Union regarding the appointment of safety supervisors for the transport of dangerous goods by road, rail or inland waterways. The scheduled date for this Directive to become effective in the countries of the European Union is 1<sup>st</sup> January 2000. In Germany the more than 30,000 dangerous goods advisors are being elevated to the status of EU safety supervisors by an amendment to the Ordinance on the Appointment of Dangerous Goods Advisors. Within the scope of the European Agreement Concerning the International Carriage of Dangerous Goods by Road, a general obligation of companies to train persons involved is to become effective on 1<sup>st</sup> January 1999.

With the exception of the ruling on immediate measures, the EC Directive on the Approximation of the Laws of Member States with regard to the Transport of Dangerous Goods by Road was implemented on 1 January through the Ordinance on the Transport of Dangerous Goods by Road and the Ordinance on

Exemptions from the Dangerous Goods Regulations; with the exception of the passages governing official aid, the EC Directive on Uniform Procedures for Checks on the Transport of Dangerous Goods was implemented on the same date through the Ordinance on Checks on the Transport of Dangerous Goods by Road and within Undertakings. In all Member States a representative number of dangerous goods transports are now to be checked according to standardised testing criteria. The road checks are to be supplemented by checks in the companies.

### Automobile Engineering

As explained at the 15<sup>th</sup> ESV Conference in 1996 a significant contribution to motor vehicle safety and environmental protection is being made in the field of design and efficiency regulations for motor vehicles through the adoption of international regulations into national law as well as through further definition of the remaining latitude in national regulations. This relates firstly to the work as a member of the UN Economic Commission for Europe (ECE) which has passed a total of more than 100 Regulations with standardised provisions for motor vehicles, their trailers and associated components, the contents of which largely correspond with EC Directives. Over 80 ECE Regulations apply in Germany. Secondly this concerns the work as a Member State of the European Union (EU) to harmonise automobile engineering regulations for vehicles intended for transporting passengers and goods as well as farm and forest vehicles, motorcycles and associated components.

Step by step, national regulations currently in force are being revised to incorporate EC Directives.

Regular technical inspection of vehicles in the EU is ordered in an EC Directive. This prescribes the intervals at which inspections on buses, taxis, ambulances, cars and commercial vehicles take place. Germany suggested that motorcycles, caravanettes and caravans should be included in these inspections, which are to apply in all

EU countries. The German Federal Government is also making urgent efforts in EU consultations to bring about a more precise definition of the scope of such technical inspections and the inclusion of clear inspection criteria and a test for heavy vehicles, which is at least comparable to the German special brake test or the new safety inspection.

The national and international laws regarding environmental protection and the active safety of motor vehicles have become more stringent during the last few years. In order to fulfil the environmental requirements of EURO I for cars, manufacturers were called upon to use state-of-the-art technology. In the case of diesel vehicles, the main area of improvement was the engine combustion system; in the case of petrol vehicles, emissions were purified using regulated catalytic converters (G-Kat). The German Federal Government provided tax concessions for vehicles with the regulated catalytic converters even before EURO I came into force (1993) which has resulted since then in a stark reduction in the quantity of classic pollutants such as CO, HC, NO<sub>x</sub>, lead and benzene despite an increase in total travel. There will be a recognisable reduction in the particles as the percentage of EURO I and especially EURO II cars (mandatory for trucks as of 1996, for cars as of 1997) increases.

In terms of passive vehicle safety, particularly crash behaviour during accidents, an EC Directive and an ECE Regulation exist on the behaviour of steering systems in passenger cars during head-on collisions. Although it has not been mandatory for EU Member Countries to apply these international regulations to date, German motor vehicle manufacturers perform crash tests on their passenger cars in order to continuously improve passenger protection.

At international level the Federal Republic of Germany collaborated with other Member States to pass two ECE Regulations concerning head-on and side collisions in passenger cars; Regulations No. 94 (head-on collisions) and No. 95 (side collisions) could be applied



from 1995 and 1996 respectively. At EC level, the Council and the European Parliament passed the Directives on side and head-on collisions with more stringent requirements in 1996; these will become obligatory as of October 1998 for all new passenger car models.

The Federal Republic of Germany is participating in the increased world-wide efforts to harmonise regulations. With regard to the introduction of the Directive on side collisions the automobile industry is making even greater efforts to further increase passive motor vehicle safety.

### Accident Statistics

There are differences in the accident development of the area of the Federal Republic of Germany before 3<sup>rd</sup> October 1990 and the area of the five new Laender. For this reason they are considered separately in the following.

In the old Laender, the number of road traffic accidents decreased by approximately 2.7 % between 1994 and 1997 to approx. 1.7 million. In contrast, total travel rose by 3.3 %.

The number of traffic fatalities has decreased since 1970 by more than two thirds; during the same period, the number of motor vehicles rose from 17 million to 41 million and total travel increased by 119 %.

Not including the new Laender and Berlin (east), there were 6800 traffic fatalities in 1994, 6,525 in 1995 and 6,126 in 1996; in 1997 there was the lowest number of fatalities since 1953 at approx. 6,000 fatalities. In 1994 3,970 car occupants died, in 1996 the number of car occupants killed decreased to 3,801.

Following German reunification in October 1990, the accident statistics in the five new Laender must be considered separately: in this region, 3,014 fatalities were recorded in 1994, 2,928 in 1995 and 2,632 in

1996; in 1997 the number of fatalities decreased to approx. 2,500.

### Accident Research

As at the previous conferences this section includes the activities of the German Federal Government, the automobile industry and the automobile insurance companies.

The Federal Ministry of Education, Science, Research and Technology has been sponsoring research and development projects to improve active and passive safety in motor vehicle traffic for many years.

In the past, the transportation of dangerous goods by road was a particular focal point of sponsorship. In this context reports were presented at the past ESV conferences on the development of the safety tanker trailer TOPAS as well as on the results of the THESEUS project (tank vehicles with maximum achievable safety through experimental accident simulation).

In the recent past a significant contribution to the improvement of active safety of road traffic has been made by fundamental research into and development of telematic systems for traffic. With the development and testing of modern data capture systems and of communication, guidance and information technologies, deficits in traffic management and on the part of road users in terms of up-to-date and complete information can be reduced. This will in future allow critical traffic situations to be recognised as they occur which will significantly reduce the risk of accident. In this context the Federal Ministry of Education, Science, Research and Technology sponsored the EUREKA project PROMETHEUS and the BEVEI project (better traffic information) with a total outlay of approx. 140 million DM. Numerous safety-relevant systems from research projects mentioned have already produced promising results in tests in demonstration vehicles.

The German Federal Government's current research framework, which was published in 1996 under the title: "Benchmark Figures for a Future-Orientated Mobility Research Policy" has the motto "maintaining mobility long-term while significantly reducing the undesired consequences of motor vehicle traffic". Improvement of traffic safety is one of the five main fields of research sponsorship. In the project network "Safe Roads" started by the Federal Ministry of Education, Science, Research and Technology in this regard the focal point will continue to be the improvement of active safety.

Under the title "MOTIV" - Mobility and Transport in Intermodal Traffic", the German automobile and electronics industry and traffic service providers have started a wide-ranging combined project sponsored by the government which has as primary objectives the improvement of mobility in conurbations and the increase of traffic safety. MOTIV builds on the results of the PROMETHEUS project which has been discontinued; in contrast to the research in the past which dealt more with fundamentals, MOTIV is orientated rather towards quick implementation - at European level as well.

In the subprojects of the combined project "MOTIV" which are part of the project network "Safe Roads", systems for increasing traffic safety and traffic flow are being developed. These include systems which provide effective support for drivers in selecting speed and vehicle-to-vehicle distance when travelling behind a vehicle up until the time when the vehicle in front stops, for warning drivers of potential traffic conflicts with other road users when changing lanes or turning and for reducing the conflict potential through active intervention. As it is still necessary to clarify basic questions of technical feasibility and find economically viable solutions, decisions regarding the further realisation of these systems will be made only after the feasibility studies have been completed.

Moreover, legal and ergonomic aspects of the various degrees of automation of vehicle guidance

functions will also be subjected to in-depth analysis in subprojects related to this subject in order to obtain information on the possibilities and limits of automation for such tasks.

In addition to the activities in MOTIV, other projects in the project network "Safe Roads", which are intended to supplement the work for improving active safety which is already in progress, are currently being approved.

One of the focal points of these projects, which will start in the near future, is better recognition and protection of vulnerable road users including investigations into how such road users can contribute most economically to their own protection. Another focal point is the investigation of how assistance systems can support drivers in an optimum manner and particularly how over-taxation and under-taxation can be avoided in this respect, how protection against rear-end collisions can be improved through warning the traffic behind sufficiently early and how protection of young road users of pre-school and primary school age can be improved through new approaches to traffic education.

The Federal Minister of Transport has continued his comprehensive research efforts; the Federal Highway Research Institute is involved to a significant extent in this work. The following will deal for the main part with the automobile engineering projects only.

As stated at the 15<sup>th</sup> ESV Conference, at-the-scene accident investigations have been continued. Each year, approx. 1000 accidents are recorded in detail and evaluated. At present a comprehensive data base exists containing the details of 14,000 accidents involving 20,000 injured persons; 24,000 vehicles are documented and there is information on 80,000 separate injuries. These data have been used in a variety of ways, inter alia for European projects on protection in head-on and side collisions and the EEVC's work on pedestrian safety. These local accident statistics are incorporated into the commission's 4<sup>th</sup> research project related to child

restraint systems, motorcycle helmet development and the standardisation of accident investigations. At present negotiations concerning the extension of these investigations are in progress with the German automobile industry.

Studies on child safety in passenger cars showed that in practice two out of three child restraint systems are used incorrectly in such a way that their effect is reduced. The main reasons for this were insufficient knowledge on the part the parents and incorrect assumptions regarding the correct method of securing children. Technical deficits were also established. From the results of the study it was possible to derive approx. 60 individual recommendations, which are directed to manufacturers of child protection systems, automobile manufacturers, the legislator and standardisation committees just as much as to the users of such systems - children and parents.

In Europe, child restraint systems are subjected to head-on collision tests in accordance with ECE Regulation 44. To date, side collisions have not been accounted for in the Regulations. The BAST is involved in the development of a new generation of child dummies which can be used for head-on and side collision tests. Parallel to this, the research group CREST (Child Restraint Systems for Cars) which is sponsored by the European Commission, has been founded with the participation of the BAST.

Various aid organisations offer transport services to wheelchair users. Transport vehicles for disabled persons, in which the disabled persons can remain seated in their wheelchairs during the journey, are used for this purpose. Crash tests performed by the BAST showed that commercially available safety and restraint systems were complicated to operate and did not provide a sufficient level of safety. The restraint system which has now been developed by the BAST enables disabled persons to be transported safely, consequently improving their ability to participate in social life. The system forms the basis for a revision of the technical provisions (DIN standard

75 078 part 2 "Restraint Systems for Transport Vehicles for Disabled Persons").

Crash tests carried out as part of the project "Safety of Vehicle Trailers for Child Transportation" indicated weak points in bicycle trailers for child transport. Test procedures for evaluating the safety of bicycle trailers have been developed with the objective of establishing a DIN standard.

Buses not used in city traffic and which do not have standing room for passengers will in future be equipped with seatbelts; this is prescribed by an EC Directive. Under this Directive, buses with a permissible gross weight of up to 3.5 t must be equipped with three-point seatbelts and buses with a gross weight of more than 3.5 t with lap belts. Certain child restraint systems, particularly those intended for children of up to 9 months and from 6 years to 12 years of age cannot be utilised correctly with lap belts alone. The BAST drew up recommendations for technical improvements.

The parts of the studies for revision of the legal requirements in side collisions which relate to head impact in the interior of the vehicle have not yet been completed. Head injuries to car occupants occur particularly frequently during side collisions. For the continued practical application of the side collision tests elaborated by the EEVC, they are being further developed along the lines of the test procedure already prescribed in the USA.

Airbags are increasingly becoming part of the standard equipment in passenger cars. The project "The Protective Effect of Airbags in Particular Sitting Positions (Out-of-Position)" studied the limits of the airbag effect in different sitting positions. During the crash test with an airbag system widely used in Germany no significant increase in the accident risk for vehicle passengers and passengers positioned close to the steering wheel was noted. The interaction of three-point seatbelts, safety belt tensioners and airbags provides a high overall level of safety for the driver.

Severe accidents resulting from the effect of airbags, as reported recently in the USA, can be excluded for Europe. The reason for this is that a general obligation to wear seatbelts has to date not been brought into force in the USA. The airbags must therefore be designed for passengers not wearing seatbelts and inflate to a large volume very quickly in the event of an accident. In contrast, due to the high "buckle-up quota" in Europe, airbags are designed as a supplementary restraint system to avoid impact between the head and components of the vehicle interior. The low volume allows it to be inflated more slowly and therefore less aggressively. The risk of injury is consequently reduced in "out-of-position" cases.

To provide consumers with objective information on passive safety in vehicles, the evaluation procedure TUB-NCAP was elaborated after many years of research and validated in real accidents by an international research association. The TUB-NCAP procedure is based on accident analysis and statistical biomechanics. The degree of fulfilment of the protection criteria is determined for the test results from various crash tests and the variables weighted in this manner are brought together in an overall safety index using a relevance structure which reflects the significance of the injuries to the various parts of the body during real accidents. The German Federal Government is attempting to realise a "EURO-NCAP" orientated towards real accident occurrences on the basis of this work.

An FE model of the human head was constructed in a co-operative project involving the Technical University of Berlin and the Institute for Forensic Medicine at the University of Heidelberg. The University of Heidelberg determined the different strength values of the various bones in the human skull. A detailed replica of the skull was completed using computer-tomographic diagrams. The ability of this model to simulate injury mechanisms during impact from a blunt instrument was validated in tests with cadavers.

A major German motorcycle manufacturer has developed a two-wheeler concept, in which the driver is secured by a belt system in a so-called protective zone. This vehicle has been examined by the BAST with regard to an exemption from the obligation to wear a helmet and with regard to active and passive safety. In the opinion of the BAST the two-wheeler tested is as safe to drive as a commercial motorcycle for a rider with a helmet. The BAST therefore recommends a provisional exemption from the obligation to wear a helmet.

Together with representatives of industry, "Guidelines for the Design and Installation of Information and Communication Systems in Motor Vehicles" have been elaborated for the safe utilisation of technical equipment in motor vehicles for information and communication purposes such as on-board computers, navigation systems, car phones, etc. This is a pilot agreement for the German position in national and international standardisation committees (DIN, CEN, ISO). Studies on telephoning at the wheel and the operation of vehicle spacing control systems also relate to this area. Further studies are carried out within the scope of research programmes by German industry and world-wide research programmes on "Intelligent Transportation Systems (ITS)".

In March 1998 a workshop took place at BAST at the request of the Federal Ministry of Transport, which dealt with a comparison of the present state-of-the-art in Germany and other countries, with current research activities and development projects as well as with the prospects of telematic technologies and driver assistance systems in motor vehicles for the improvement of traffic safety. Experts from industry, research and politics were given the opportunity to exchange views on and discuss four main subjects: German and international activities, the current position in research regarding driver assistance systems, opportunities and risks as well as problems for market introduction. At the conclusion of the workshop there was a podium discussion in which the main subjects were treated with regard to fields of activity for the private economy and public institutions.

An international workshop on the same subject with participation of experts from the Netherlands and Great Britain is planned for a later date.

BASt is participating in the international activities of the IHRA related concerning the subject of ITS on behalf of the Federal Ministry of Transport. An initial step was the completion of a survey, in which 17 research projects on the topic of human/machine interface were evaluated by Germany.

A committee of experts in Brussels is dealing with questions regarding the possibilities of implementing "Telematics in the Transport Sector". Fields of action are being differentiated according to public and private interests. Another committee is concerned with questions relevant to safety in connection with the introduction of new technologies in motor vehicles, e.g. how far can and should technical equipment intervene in the personal responsibilities of the driver? Should new technologies for improving traffic safety be introduced on a mandatory or voluntary basis?

Pilot projects on technical equipment in motor vehicles are the focal point of the common activities of EU Member States. Under the overall control of the Netherlands, tests are being carried out on an intelligent speed controller (ISA - Intelligent Speed Adapter), which serves to select speed according to the situation via road controls.

The BASt is currently having tests carried out on the safety aspects of driver assistance systems such as Systems for Controlling Driving Dynamics and Systems for the Automatic Driving of Motor Vehicles. For this purpose the dynamic driving potential of the model for regulating driving dynamics was investigated in a simulated test and error simulations carried out. Using this electronic system with automatic regulation of the vehicle brake system as an example, the procedure for safe design of mechatronic systems was discussed and the basic approach to risk analysis presented. Recommendations for necessary regulations in terms of

the approval and technical supervision of such systems, taking into consideration national and international laws, are being derived by the researchers. These concern general requirements for electronic systems as well as special requirements for the brake systems in motor vehicles. Systems for automatic driving will be examined in a study being started at present on legal and traffic safety and safety with regard to interaction and the system itself. Based on consultations with experts and technical simulation studies, recommendations are to be derived for legal regulations and technical standards.

Since no clear figures are available to date on failure frequencies and the scope of failures in electronic systems in motor vehicles relevant to safety or the environment, a random study was performed on electronic systems (ALS, airbags, engine and transmission control). For this purpose readings were taken of the fault memory in the systems in order to determine the scope of the defects which occurred and to estimate the effects.

The results of the research project were the subject of a discussion of experts. The conclusion derived from the results regarding the necessity of regularly checking electronic systems in motor vehicles proved, however, to be controversial. More discussion of this is required. The participating experts agreed that, in a current suggestion for a Directive made by Germany, which is being discussed at present in Brussels and Geneva, a suitable type approval regulation had been reached which takes into account the future technical inspection of these systems.

The dynamic behaviour of motor vehicles is a significant aspect of active safety. Evaluation of this behaviour is difficult, because the overall system is characterised by the interaction of the driver, vehicle and environment and each element is already complex in itself. The objective of a research project carried out by the BASt was to examine the interrelationship of subjective driver perceptions and objectively measurable variables which characterise the handling of a passenger

car. So-called open-loop and closed-loop driving tests were performed with the same vehicle; the handling characteristics were, however, changed by modifying the vehicle parameters. The test drivers consisted of 40 "normal drivers" and 12 "professional drivers", who evaluated the driving characteristics on the basis of a prescribed evaluation method. It was possible to ascertain that the subjective evaluation best correlated with the time delays between steering wheel angle and yaw velocity and between steering wheel angle and lateral acceleration as well as with the sideslip angle. The roll velocity also had an effect on the driver's evaluation. Although the validity of the interrelationships found was proved for the investigated vehicle versions and driving situations, further studies on other vehicles and in other situations are required to discover whether the results apply generally.

The primary benefit of the accident data recorder (ADR) is its contribution to clarifying the causes of traffic accidents. A research project commissioned by the BAST investigated whether further benefits for accident research in the form of analysis of the chronological events immediately before a collision (pre-crash phase) are possible with such instruments. It was seen that the ADR always provides objective data independent of the road condition or activation of ALS and that it can increase the degree of information obtained for individual characteristics (such as braking and/or steering reactions of the driver before an accident). This allows a more precise analysis of motions and events in the pre-crash phase even when the use of conventional reconstruction procedures provides no or insufficient information. Overall, the use of ADR in combination with conventional accident analysis procedures can improve the reliability of data records and the gains in knowledge for accident research.

In the Federal Republic of Germany the maximum permissible speed for passenger cars with trailers is limited to 80 km/h. In view of the fact that there are a large number of car-trailer combinations which demonstrate safe handling characteristics at higher speeds

and also that higher speeds are permissible in other countries, the BAST investigated within the scope of two discussions of experts whether the speed limit for passenger cars with trailers could be increased from 80km/h to 100km/h on autobahns and which aspects have to be taken into consideration in this context. A corresponding major test is planned in the course of further considerations.

Due to the findings of the two discussions of experts a paper has been drafted by the BAST containing a concrete suggestion regarding the obtaining of a temporary special permit for car-trailer combinations allowing them to drive at a maximum speed of 100 km/h on federal trunk roads (including a certification sample required for this purpose).

According to the German Traffic Regulations (StVO) the speed limit for motorcycles with trailers on roads outside built-up areas (including autobahns) is 60 km/h. On account of a discussion of experts at the BAST, an increase in the present speed limit of 60 km/h is recommended for motorcycles with single-axle trailers, even though some questions remain open regarding the driving dynamics for such vehicle combinations at higher speeds. To date, however, no information is available on what the upper limits are, to which the permissible speed for all motorcycles with trailers could be raised without risk regarding driving dynamics.

By contract to the BAST, a research project for the improvement of bicycle traffic safety was carried out in 1995, in which, inter alia, the question as to which strength requirements should be made for parts of bicycles relevant to safety was considered. The results of this study - which are also to be incorporated into the corresponding German Standard (DIN 79100) - were the subject of a subsequent discussion of experts. It was seen in this regard that the strength test requirements for bicycles planned for the German Standards were insufficient. The experts recommended determining the operating loads for a number of representative bicycle models. A corresponding study was carried out by

contract to the BAST in 1996 - 1997. The effective operating loads of a total of 17 bicycles were determined on bicycle paths, paved roads and on rough roads. Supplementary to this, special occurrences (emergency braking manoeuvres, minor falls) and misuse (overloading, driving over potholes and curbs) were also taken into consideration. The loads determined in this more recent study provide a good basis for drawing up strength requirements and test conditions for the structurally durable design of bicycles and bicycle parts.

Defective shock absorbers can change the driving behaviour of motor vehicles. For this reason technical inspection of shock absorbers is part of the main safety inspection required under Sec. 29 of the Motor Vehicle Construction and Use Regulations. Various parties have requested that this visual test is supplemented by an objective testing method. In a number of studies the frequency of defective shock absorbers as well as their role in the occurrence of accidents was therefore estimated. Moreover, the BAST also held two discussions of experts on this subject. The results gained so far must still be verified.

Retreaded passenger car tyres account for 2 % of summer tyre sales in Germany and for 11 % of winter tyre sales. The retreading process offers an active contribution to environmental protection and conserves resources. A recommendation by the EU Commission provides for the prohibition of the disposal of old tyres as waste from the year 2000; the significance of retreading tyres is therefore growing. It must be ensured that no safety deficits result from the use of retreaded tyres in countries such as Germany where there are no speed limits on the autobahns. Uniform standards for retreading are being discussed in the ECE. The BAST has studied the influence of carcass age, repair of punctures and classification of the permissible speed for retreaded tyres in 180 tests.

The age of the carcasses to be used should not exceed 6 years. Repairs should be regarded critically and reclassification in a lower speed class is recommended. It

also appears problematic to allow a maximum speed of 240 km/h for retreaded tyres.

The research efforts regarding the efficacy analysis of exhaust tests on diesel vehicles and passenger cars with regulated catalytic converters reported at the last ESV Conference are being continued. Final results are expected in the coming year.

Within the scope of the research project "The Effects on Traffic and the Ecology of Overtaking Prohibitions for Trucks on Autobahns", the effects on traffic safety inter alia were studied. An analysis of the accidents in a before/after comparison was made on three autobahns with one-way roadways amounting to a length of 430 kilometres; approx. 10,600 accidents were evaluated. It was not possible to establish any fundamental effects on traffic safety resulting from an overtaking prohibition for trucks. The following conclusions appear justified: the overtaking prohibition for trucks can be expected to have a favourable effect on traffic safety, particularly under certain framework conditions, inter alia when the involvement of trucks in accidents is significantly higher than their percentage in traffic, when a steep slope is present or when the sections in question are preceded by a reduction in the number of lanes. There are indications that a limitation of the length of the section in which overtaking is prohibited to approx. 10 kilometres is also favourable from the point of view of traffic safety.

The German automobile industry is increasing its work on developing innovative lighting systems as a further contribution to improving active vehicle safety.

BAST performed studies on pollutant emissions and fuel economy when the engine is shut off for a short time and investigated how long the engine has to remain shut off compared with an idling engine to compensate for the increased pollutant emission and fuel consumption which occur during the starting of a motor. The study showed that the minimum shut-off times for advantages to be gained from the temporary shut-off differ for the various

exhaust constituents and fuel economy. For the BAST's emission test vehicle the times were several minutes in the case of hydrocarbons with the exception of carbon monoxide, only a few seconds for nitric oxides and approx. 10 seconds for the fuel economy. No tests were performed under actual traffic situations. The results were obtained exclusively using the emissions test vehicle with a warm engine and without erroneous operation such as depressing the throttle while starting the engine. The applicability of these conclusions to other vehicles - particularly vehicles with other engine, mixture generation and emission control concepts - is therefore only permissible to a limited extent if at all. It can be assumed, however, that the order of magnitude of the results applies to comparable vehicles equipped with catalytic converters.

During the past few years the rescue services in the Federal Republic of Germany have become a nationally and internationally acknowledged system.

According to continuous projections the rescue services had 9 million assignments in 1996/1997; of these, 60 % consisted of ambulance transports (urgent and non-urgent) and 40% rescue operations (with and without emergency physician). This means that, on average, every 9<sup>th</sup> resident used the rescue services once a year. The number of rescue operations accompanied by an emergency physician is increasing continuously: in 1985, 32 % of the rescue operations were accompanied by a physician; 12 years later the figure was 48 %. The response time, i.e. the period of time between the reporting of the emergency and the arrival of the rescue vehicle at the accident site was on average 7.7 minutes.

Approx. every 11<sup>th</sup> emergency assignment (9 %) involved a traffic accident. The percentage of the total number of emergency assignments made up by traffic accidents has decreased continuously during the course of the years. 20 years ago it was still 27.2 %.

The German Insurance Association has systematically enlarged its databases on personal injury

road accidents during its accident research which is carried out by the Institute for Vehicle Safety.

Based on a previous evaluation of 15,000 car-car crashes, approximately 1,000 accidents with seriously injured occupants were evaluated. The data are now in a database which is accessible for accident investigations and have been comprehensively analysed. It could be seen that future developments in the field of safety must be designed to take greater account of angular head-on collisions and the protection of elderly persons. The optimisation of side protection and foot space in cars must be taken into consideration in the development of vehicles.

The evaluation of approximately 1,200 pedestrian accidents has now been completed. Material solely on collisions between pedestrians and cars constructed in 1996 or later is at present being compiled to supplement this investigation. The objective is to be able to quantify the influence of new automobile body shapes on the accident sequence and origin of accidents.

The German Insurance Association research study "Improvement of the Protection of Children in Cars" was completed under contract to BAST. It was seen that, despite considerable improvements in child protection systems, there are still deficits, above all in their operation and use by parents. Misuse of child seats (incorrect installation of seat, incorrect securing of the child in the seat) was ascertained in two-thirds of the cases examined. Questioning of 150 test persons revealed that the rate of incorrect operation (between 60% and 80% in the case of conventional systems) could be reduced to approximately 4% through the introduction of ISOFIX.

In the ISO work group for the development of a Test Standard for child seats, various child seats were for the first time tested in side collisions.

The continued investigation of airbag accidents has shown that the problems regarding rear-facing child seats



and out-of-position front seat occupants can be solved to a large extent using an "intelligent airbag". It was also established that raising the actuation threshold of the airbag to 25-30km/h would on the one hand lessen the injuries caused by the airbags (grazes, 1st degree burns) and on the other lower the costs caused by an unnecessary release of the airbag; the protection of the car occupants would at the same time not be reduced.

Under the EU research project "Whiplash", the following three topic areas were dealt with:

- 500 rear end collisions were evaluated medically and technically. It was confirmed that a high percentage of the slight cervical vertebrae injuries which occur at low collision speeds cannot be explained biomechanically;
- particularly well-documented cases were reconstructed in detail, in order that they could be repeated in crash tests;
- sled tests with volunteers were supposed to provide new information of the kinematics of vehicle occupants in rear-end collisions, in order to better understand the biomechanics of such injuries and to validate future cervical vertebrae dummies.

In the field of motorcycle safety, the crisis situations leading to crashes were investigated in 500 collisions between motorcycles and cars. The findings from the study were incorporated into a leaflet for motorcycle riders and a video film which is made available to interested persons.

The focal point of the work in commercial vehicle accident research was the improvement of rear underride protection. In addition to this a study was drawn up on the origin of accidents involving unprotected road users which occurred while commercial vehicles were turning; this study showed that a considerable number of such collisions could be avoided through electronic aid devices for heavy vehicle drivers.

You will find the contributions of the German car industry in the various technical seminars at this conference.

We will follow the talks given over the next few days with great interest. We would like to express our wishes that this year's ESV conference is a complete success.

# The European Enhanced Vehicle-Safety Committee (EEVC)

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**Bernd Friedel**

Bundesanstalt für Straßenwesen

It is again my pleasure to present the Status Report for the EEVC and to describe the work we have done since the last conference. One important step was the change of the name of our committee. According to the shift of the focus of the ESV conferences from concentration on the development of experimental safety vehicles to broader issues of motor vehicle safety there was since years a parallel shift in the work of EEVC. The new name European Enhanced Vehicle-Safety Committee reflects this change and keeps the acronym EEVC.

## Frontal Collision

The Working Group 16 was created with the tasks of continuing the support and development of the EEVC offset deformable frontal impact test procedures and also to provide the real point for the European contributions to the work of the International Harmonized Research Activities (IHRA) Working Group on Advanced Offset Frontal Testing. The terms of reference were formulated in the beginning of 1997. One of EEVC's obligations to the EC was the finalisation of the foot certification procedure. This task has been completed and the EEVC recommended certification procedure comprises impacts with a defined pendulum to the toe and to the heel without shoe together with a further impact to the heel fitted with the specified shoe.

Other tasks to be considered in relation to the EC directive of frontal impact are the evaluation of the potential benefits of an increased speed and the potential benefits of an extension of the scope of the directive to N1 vehicles and M1 vehicles between 2.5 and 3.5 tonnes. In addition, the accident analyses may provide information for the footwell intrusion measurements.

This EEVC working group is also considering future developments of revised barrier faces and a methodology for the evaluation of barrier faces. As part of the contribution to the IHRA work, WG 16 is considering the relative merits of a mobile barrier test procedure.

## Side Collision

The work is continued to develop a repeatable and meaningful head impact test procedure. A paper on this work will be presented at this conference in which

the relative benefits of free flight and linear guided impacts are investigated. The provision of airbags in the head impact zone in some cars is being taken into account by the working group as there is no wish to discourage innovative and potentially beneficial safety measures from being introduced.

The work of Working Group 13 was also addressed to the development of test methods for evaluating and comparing the performance of different existing side impact barrier faces. In a second paper the results of this comparison will be presented during this conference.

In a second paper, the development of these test procedures and some pilot study results will be presented. Previous experience has shown that different designs of barrier face can give different results in full scale test impacts. The tests being developed are intended to be able to evaluate different designs under realistic conditions. A full test programme in which the performance of seven different barrier designs has been planned for the coming year.

With regard to the EU Directive 96/27/EC on side impact protection the working group will evaluate the potential benefits of an increased test speed and the need to change the mobile deformable barrier face height and/or ground clearance. In addition EEVC will also review the need for a pole side impact test. The initial approach to these topics will be an analysis of accident data bases in conjunction with a review of current test experience.

## Compatibility

The EC Commission is funding the studies of this working group through a larger research project. The project has started in the middle of 1997; the running period will be two years.

This project will provide for the start of a scientific approach to the question of compatibility. At the beginning, effort will be concentrated on the most important impact types: passenger car to car frontal and side impacts. During this work, consideration will be given to the implications for pedestrian and other types of impact but they will not be directly addressed.

The work will cover three main activities:

- Data from in depth accident studies will be used to

identify the most important problems related to compatibility.

- Typical accident configurations will be replicated by carrying out experimental car to car impacts. These crash tests should help to identify the major problems occurring when two cars impact.
- Computer simulation modelling will be used to study the effects of changing the effective stiffness and mass of two cars impacting.

Vehicle incompatibilities can be observed in vehicle structure (stiffness and geometry) and vehicle mass.

Up to now mass incompatibility has been identified and quantified in a large number of studies. One task of the compatibility project should be to come to a better description of the effects and better established figures concerning the quantification of this effect. The most successful method in this field seems to be the analysis of overall accident statistics for vehicle groups of similar structure. A comprehensive structural survey for passenger cars shall help to define those vehicle groups of comparable vehicle structure.

About the results so far achieved a detailed report will be given at this conference.

Beside this programme the Working Group 15 provides scientific input to the IHRA working group on the same topic. A cooperation with a BRITE-EURAM project in the same field is established.

### **Dummy Development**

Working Group 12 was originally created with respect to the development of frontal impact dummies. The terms of reference are now enlarged to achieve the development of universally acceptable advanced anthropometric adult crash dummies for various impact directions. Secondly, with this working group the EEVC contribution to the IHRA international working group on Biomechanics is assured.

The frontal impact dummy activities of WG 12 are carried out through the EC funded ADRIA consortium. Main activity is the evaluation of the advanced frontal impact dummy THOR developed in the United States. The evaluation results will be reported to EEVC WG 12. Results will be available in the summer of 1998.

Concerning the initiative of ISO for the development of a Harmonised Side Impact Dummy, EEVC proposes to NHTSA that IHRA should take the lead in such a project. The work to be carried out should include review of existing biomechanical data, desirable features based on current dummy experience, revision of existing test devices against these

biomechanical data and desirable features, and the latest information on injury tolerances.

In Europe recently the so-called SID-2000 consortium was established, dealing with future side impact dummy development activities. The work in this consortium is funded by grant from the EC within the so-called BRITE-EURAM program. The consortium will enhance side impact dummies for improved occupant protection beyond the year 2000. EEVC was informed that results of this European SID 2000 will be made an integral part of the ISO Harmonised Side Impact dummy developments.

### **Pedestrian Protection**

Working Group 17 Pedestrian Safety was established in 1997, with the tasks to:

- Review the EEVC WG 10 test methods published 4 years ago and propose possible adjustments taking into account new existing data in the field of accident statistics, biomechanics and test results
- Prepare the EEVC contribution to the IHRA Working Group on pedestrian protection.

The EEVC WG 10 test methods consist of sub-system tests to the bumper, bonnet leading edge and bonnet top. Concerning the first task of WG 17 accident data were analysed dealing with bonnet leading edge injuries. The UK data show a shift from upper to lower leg injuries, but upper leg including pelvis injuries are still frequently seen. The German data show a decrease in the percentage of injuries caused by the bonnet leading edge. This is confirmed by a French study. Looking to pedestrian injuries in accidents with a car impact speed up to 40 km/h, it was found that the bumper is the most important car area, followed by the bonnet top and finally the bonnet leading edge. Based on these accident figures, the bonnet leading edge test method is reviewed in order to define a better relation between modern car shapes and subsystem test conditions. A series of accident reconstructions will be done to investigate the appropriate acceptance level for the bonnet leading edge test requirements.

The feasibility of the test methods is studied also for vehicles with extreme dimensions, like 4x4 off-road vehicles.

The impactors used for the sub-system tests have been improved, however without fundamental changes to the design principle.

The European input to the IHRA activity on pedestrian protection was mainly focusing on accident statistics.

## **Underrun Protection of Heavy Goods Vehicles**

During the last ESV conference the results of Working Group 14 were reported. A proposal for further funding by the EC commission was unfortunately not successful. The high priority for further development was underlined to the High Level Group on Traffic Safety at the end of 1997. Further decision-making of that Group is expected for March 1998.

The work so far achieved was presented at the SAE TOPTEC Conference about Heavy Vehicle Underride in April 1997 and was well received.

Our intention is to extend a closer cooperation on this issue with the USA and Australia.

At the end of 1997 the main committee of EEVC decided to enlarge the terms of reference of this working group also to deal with the necessary research to improve existing regulation on rear underrun protection.

## **International Cooperation**

EEVC has continued the links of cooperation with the EC and the ECE. The steering committee has noted interest in the EC paper on "Promoting Road Safety in the EU Programme for 1997 - 2001". For the 5th RTD framework we have proposed research activities on the following issues:

- downsizing and compatibility
- biomechanics

- vulnerable road users
- evolution of frontal and side impact beyond October 1998

The scientific contributions of the European community to the international harmonised research activities within IHRA are being made through the EEVC. In particular, the EEVC is actively contributing to the work on frontal protection, compatibility, dummy development and pedestrian protection as has already been mentioned.

Our scientific knowledge is continuously transferred to the ECE in Geneva, particular items are front and side impact, interior head protection, and improvement of front underrun protection for trucks.

We are well prepared to continue our international cooperation, not only in Europe, but also with North America, Japan and Australia. The exchange of scientific knowledge is a solid foundation for improving existing regulations.

## **Outlook**

The new name European Enhanced Vehicle-Safety Committee should be understood as our firm involvement in all questions relating to vehicle safety. We are convinced that developing technologies offer new possibilities for improving the safety of road vehicles.

We confirm our willingness to continue to cooperate internationally including our active participation in the ESV conferences.

# France

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Jean-Pierre Médevielle

French National Institute for Research in Transportation and Safety

## INTRODUCTION

This report, as the last one, covers the road safety activities concerning France, and in particular these having repercussions on the safety of vehicles for these last years.

On this subject, we have to remind that even if the national level keeps a wide autonomy of decision, now we can not conceive it without a range of decisions places or preparation of decisions at an European, international level but also at a local level.

### I. The progression of road safety in France

Since the last ESV Conference, figures show obviously an amelioration on the important datas, but the public authorities and all this field actors keep being worried if we compare our results, with all the usual precautions, to other countries, and particularly European ones.

The number of dead within 6 days\* is fallen below the 8 000 deaths (7 987 in 1997, 8 412 in 1995) ; likewise for serious injuries (35 716 in 1997, 39 257 in 1995), slight injuries (133 742 in 1997, 142 146 in 1995) or casualties (125 202 in 1997, 131 987 in 1995).

In fact, behavioral elements were observed, as the relative stability of real practiced speeds (at on high level), the relative stability of seat belt fastening rate when the optimum rate is far to be reached, and we even see in the public opinion a relative loss of conscience concerning the road unsafety problems, or a growth of accidents involving motorized or not two-wheeled vehicles, or the contrasted evolution of these results with regards to the concerned networks types (relative defacement on the highway, stability on the local network, relative amelioration on the national network, highways excepted). It results that the public authorities consider it necessary to give a new impulsion.

### II. Road safety policy

This new impulsion was decided during the last meeting of the Interministerial Road Safety Committee on

the 26 November 1997, whose target is to share by two road unsafety in France in the next 5 years (1998-2002).

To reach this objective, an innovative and ambitious policy is necessary.

It will be developed on three main trends:

- to lean on young people and their capabilities to promote new behaviors. Road users as pedestrians or drivers, they are the first victims of the road unsafety (more than 28% of deaths are less than 25 years ; each day, 6 children or young people die on the road). The prevention, awareness and training actions that have to be sustained all along the life, will be strengthened.
- To develop partnerships around the objectives decided by the government. In order to have the means for answering the growing social demand of safety, the government will have to mobilize all the societal actors, the State Services of course, but also the companies, associations, local communities and insurance companies.
- To guarantee the freedom to move around safely. Driving is certainly a private activity, but it is above all a social act that has to respect the basic civic values as taking into account the others, and the liberty to move around safely. This means simply, clear and intangible rules.

Four measures groups were decided :

#### To increase the awareness and train all along the life

- To educate before to be old enough to get the driving licence :
  - training actions will be developed from the childhood in the scholastic and the extra-curricular framework.
  - it will be possible for all the young people to pass the general theoretical examination ("le code") when they will be 16. The content of this examination will be modernized.
- To train the young drivers :

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\* within 30 days in 1997 : 8 444

- a 6 hours time rendezvous for evaluation and training will be proposed to the young drivers after one year of driving (free for young people) ;
- a compulsory additional training will be brought in for the young drivers authors of serious infringements to the Highway Code (license points training course), besides the usual sanctions.
- A continuous training rendezvous every 10 years for the drivers will be experimented in several counties.
- To reorganize and clean up the working of the companies dedicated to the driving teaching, and to improve their services quality.

#### **To guarantee the freedom to move around safely**

- The excessive speeds are the first cause of road mortality. A 5<sup>th</sup> class measure (at the maximum : 3 months' driving ban and 10 000 FF fine) will be brought up in order to punish the drivers who will exceed the speed limits more than 50km/h. This contravention will be transformed in offense if the same infringement is observed into the year.
- The imperfections of the control / sanction system, when the control is realized with an automatic device, can allow people to avoid the sanctions, and that leads to inequalities in front of the law. A legislative disposition concerning the car owners pecuniary liability will be finalized.
- The sanction process will be simplified by the cancellation of the administrative commissions for the driving license suspension. The judicial process becomes the general rule, and the administrative process taken by the Prefect is reserved to the more serious infringements (drink-driving, failure to report an accident).
- In order to improve the safety of the moped riders, the mopeds will be registered.
- The research of illicit substances will become compulsory in the cases of fatal accidents. So, the knowledge on the substances affecting the control of the vehicle will be improved. In the same time, a pictogram will be printed on the medication packaging when these substances can have negative effects on the driving

#### **To improve the infrastructure safety**

- The cyclist safety will be strengthened (creation of special spaces before the traffic lights, authorization to ride in the pedestrian areas...) and the Highway Code will be modified in this way.
- Restraints devices (crash barriers) less aggressive for the bikers will be studied and their use developed

- A systematic safety audit for the new road projects will be enforced in order to be sure that they contributes to the users safety and they incite the drivers to a safe driving.

#### **To support the local policies**

The Interministerial Committee propose to the "Départements" (equivalent to the Counties) to set up a local organization in order to improve the involvement of all the partners and to have a better assessment of the leaded policies.

A part of the measures concerning the road users training and the drivers training comes from the results of the Consultation on the training launched in 1996, and that explains also the necessity of a partnership with the companies involved in road safety.

In the same time, we have to remind that France participates to the preparation of European policies, statutory ones included, this being attested by its active attendance in the European high level groups involved in road safety or intelligent transportation systems, or in the works of the European Economics Commission of UNO.

It is the same for the international activities concerning road safety within the OECD, the ECMT, or concerning the vehicle field related or not to EEVC or CEN, for the IHRA and ISO activities.

### **III. The progression of Research and Development**

Far be it from me to repeat what was previously said on road safety at an European level in the framework of the 4<sup>th</sup> FRDP (Framework Research and Development Program). The last two years were dedicated to the preparation of the 5<sup>th</sup> FRDP, that should be approved this year, safety being one of its major concerns, at the level of research for a sustainable and safe transports policy, but also at the level concerning research on vehicles.

In the same time, the national effort was continued through the activities of the national Program PREDIT2 (1996 - 2000) on the different fields of the themes "safety and ergonomic" and "intelligent transportation systems", that is to say :

- accidentology and biomechanical studies.
- the modeling of collision phenomena,
- imminent hazard warning systems and the localization of accidents,
- training and safety tools,
- vehicle design and infrastructures.

In the same time, besides PREDIT 2 themes, the scientific and technical concerned community, particularly in and around INRETS, has studied thoroughly :

- the introduction of new methods concerned with providing solutions to the problem of serious injuries in addition to that of fatalities with attention being given to relationships between ethics and science (Rhone's Road Accident Trauma Registry acknowledged by the French Health Ministry, the taking into account of the Helsinki's agreement concerning the experimentation),
- the compatibility between vehicles using the same infrastructure,
- multidisciplinary work on the trio infrastructure-vehicle-driver/passenger, not forgetting the problem of our ageing society,
- the progression of our understanding simulation - modeling around the creation of a knowledge dedicated to the research and development.

## CONCLUSION

You will be presented with a large number of French works during this conference, from the manufacturers, the equipment suppliers and the research institutes, and I think that they will demonstrate the challenge France intends to take up with respect to road safety.

# United Kingdom

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**Keith Rodgers**

Department of the Environment Transport and the Regions

## Introduction

I am delighted to be here in Canada to present the United Kingdom's Status Report for the second time at an ESV Conference. Our Chief Mechanical Engineer, Mr Malcolm Fendick, sends his apologies for not being able to be with us today and sends his best wishes for an informative and successful conference. I will in the next few minutes explain the UK's current position with regard to vehicle safety and some ideas on how these might develop in the future.

## The UK's Road Safety Target

Since my last report the UK has been working hard on developing a strategy for a new casualty reduction target. Our current target is due to be replaced in the year 2000. There has been a consultation exercise carried out within the road safety community in the UK and these views are now being taken into account in formulating the way forward.

Although our current target has been most successful in focusing the road safety communities' attention on the measures needed to reduce casualties there was a flaw in that there was no discrimination between killed and serious injuries on the one hand and slight injuries on the other. What we are now finding is that the percentage reduction required for killed and seriously injured is being met, but the numbers of slight injuries are not reducing giving the impression that the target is not being met. For the future the decision has been made to stratify the target for each type by severity of casualty and, perhaps, road user so that it will be easier to see where the policy is having the most effect.

One of the main areas providing a step change in road casualty reduction is that of new technology now being introduced into the vehicle fleet. Primary safety has benefited from improvements in anti-lock braking, enhanced by better tyre and suspension technology. Developments in secondary safety include improved structures, better restraint systems and pedestrian protection. Motorcyclists have benefited from improved helmets and there is potential for both improved primary and secondary safety but these areas have proved most difficult to cater for. I show here a table of the

improvements to road casualties that we estimate could be achieved from various actions.

By the next ESV our target will be defined and in place. Whoever makes this report in 2001 will be able to tell you about these and the initial reduction towards the target.

## EURO NCAP

In my last report I informed you about the UK's intention to carry out research into the feasibility of a UK NCAP scheme. Even at the last conference these plans were developing and the Swedish Government made overtures at that time to join together with the UK in developing a joint NCAP scheme. In December 1996 an international grouping was formed with the UK, Sweden, the FIA, the International Consumer Groups, and the UK motoring Clubs. The title adopted for this grouping was Euro NCAP.

In February 1997 Phase I of Euro NCAP published the results of tests on seven super mini sized cars using a new system for informing the consumer about the crashworthiness and pedestrian protection of cars. This utilises a star system that goes from 1 to 4 stars, and is backed up by more data, which shows the levels of protection for various body regions for the driver and front seat passenger, as well as showing the risks of injury to adult and child pedestrians from the front of the car. Instrumented child dummies, fitted in child restraints, are used to determine the level of protection provided for children.

Phase 2 was launched in July 1997 covering 12 family sizes saloon cars, and Phase 3, launched on 28 May, is covering 12 smaller family saloons. The results of these series of tests can be seen in the exhibition on the NCAP stand. Future plans include our fourth series of results to be released in September 1998 covering large saloon cars.

The original membership for Euro NCAP has been increased now with the inclusion of the Dutch Government and a regrouping of the motor clubs under the FIA<sup>1</sup> and AIT<sup>2</sup> and the German motor club ADAC<sup>3</sup>, joining as a single member. Perhaps the most exciting

<sup>1</sup> Federation Internationale de L'Automobile

<sup>2</sup> Alliance Internationale de Tourisme

35 <sup>3</sup> Allgemeiner Deutscher Automobil-Club e.V.



development has been that DGVII, on behalf of the European Commission, has now promised support for Euro NCAP and they have provided funding in 1997 and 1998.

One of the main aims of the European Commission supporting Euro NCAP is to encourage greater funding to enable whole market sectors to be tested at one time. For the future Euro NCAP will probably move away from large group tests but will be aiming to test all new models as they come onto the market.

The UK is investigating the potential of applying NCAP principles to primary safety features. This is seen as a logical, but difficult, extension of the present programme and one which would aid still further consumer choice.

I would now like to come onto those areas of legislation concerned with vehicle safety, which the UK has been dealing with over the last two years.

### **Electronics**

The growth in the application of electronic control of vehicle systems, and the complex relationships that may be present as a result, are raising concerns in Europe. The rapidly developing technology presents new problems for the safety evaluation of new vehicles under the European Type Approval system. A specialist UNECE ad hoc group, chaired by the UK, is considering the possibilities of a new Type Approval methodology for these systems.

### **Mini Bus and Coach Seat Belts**

Since we were in Melbourne hearing about the Australian experience over coach seat belts our national regulations have been amended to require vehicles transporting children to have seat belts fitted. There were some spectacular accidents involving children that made these changes inevitable, including one involving the deaths of 12 children in late 1993. It was decided that these changes were to be retrospective and therefore mini buses and coaches not originally fitted with anchorage points for seat belts have to comply. As you can imagine this has provided a very difficult technical situation which we are still managing in a detailed way. These vehicles are now coming up for annual inspections and it is a considerable challenge to determine which installations are acceptable.

### **Bus and Coach Safety**

We have a range of research projects supporting bus

and coach safety for the current negotiations within the European Union on a new directive for large PSVs. The areas being investigated include escape routes, fires, barriers, standing passengers and a whole spectrum of other issues. The basis for our investigation starts with accident data but then proceeds through design solutions and advice to operators for any retrospective changes.

### **Truck Accidents**

Despite having legislation governing the construction standards of heavy vehicles, accidents involving trucks are still of concern. Anti-lock braking has been a mandatory requirement on heavy towing vehicles and their trailers for several years. Publication of the long awaited revision of the European Braking Directive provides us with the opportunity to consider an extension of anti-lock braking requirements to all "working" vehicles over 3,5 tonnes. The UK is also involved in a comprehensive evaluation of the relationship between the design and in-service braking performance of heavy vehicle combinations. It is intended that this work will lead to improved road safety by changes to international construction standards.

Accidents involving both trucks and passenger cars are another concern, and the UK is fortunate in having legislation for effective sideguards, rear under-run guards and spray suppression equipment on most heavy trucks. As car structures and their safety equipment improves there are new opportunities to protect car occupants. Work continues for the collection of accident data and details of occupant injuries both in cars and trucks. This has led to work on improved cab strength testing procedures, as it is evident that the compulsory wearing of seatbelts by truck drivers will only be fully effective if the cab structure maintains a survival space. Of course these studies also point to the fact that there are real problems over crash compatibility between cars and trucks, as well as between trucks within the UK vehicle fleet.

### **Crash Compatibility**

To attempt to address these problems the UK has an existing compatibility programme, which has been running for two years and will be used to support the work of EEVC WG15 and IHRA<sup>4</sup>. Work so far has been to investigate the extent to which physical parameters affect incompatibility and so hopefully being able to define the problems and indicate possible solutions. This work has been carried out using crash testing and computer modelling.

From initial studies elsewhere of the various national vehicle parcs it is clear that the proportions of types of vehicles vary considerably from country to country. It has always been clear that there are more small cars in Europe than in the US, but what was not so evident was the effect of the sport/utility market sector in the US.

Modelling work is being developed in the UK for feeding into EEVC WG15. The US are constructing a series of finite element models of generic vehicles in the US vehicle parc. These models are to be made available through WG15. Models of the vehicles which are common to the US and European vehicle parc will assist in work to harmonise any test protocols that are

developed. This work is ongoing and will be reported to the conference in other sessions.

### **Conclusion**

The UK continues to put a great deal of priority into improving the safety on our roads. However much of what needs to be achieved requires international co-operation both in the fields of research as well as agreeing on new regulations which have to be adopted Europe wide and hopefully can be internationally harmonised. The ESV continues to be a source of inspiration and a means of establishing cross-links with what is going on elsewhere in the world. I look forward to the rest of the conference. Thank you very much.

## POTENTIAL KSI SAVINGS BY 2010 IN THE UK

No	Measure	% Potential Reduction in KSI by 2010				
		Car Occu- pants	Pedestri- ans	Cyclists	Motor- Cyclists	HGV Occu- pants
1	Side impact protection	7.00				
2	Frontal impact protection	7.00				
3	Euro NCAP	15.00	10.00			
4	HGV energy absorbing front underrun	6.00				
5	Seatbelt-ignition interlocks	1.00				
6	Improved compatibility	0.40				
7	Smart adaptive restraints	0.50				
8	Improved vehicle lighting include DRL	0.70	0.70	0.40	0.70	0.70
9	Compulsory ABS for HGVs	0.90	0.30	0.40	0.40	3.00
10	Compulsory ABS for cars	0.20	0.60	0.60	0.60	
11	Rear impact for cars	0.10				
12	Intelligent HGV speed control	0.20	0.10	0.20	0.40	3.00
13	Electronic brake control (EBS)	0.10	0.20	0.20		
14	Improved child restraints ISOFIX	0.40				
15	Stronger, larger HGV sideguards	0.10	0.10	0.90	0.05	
16	Improved fire protection	0.20				
17	Stronger HGV rear underrun guards	0.10				
18	Improved safety steering wheel	0.01				
19	HGV front and side vision		0.10	0.20		
20	Fitment of ABS to all motorcycles				1.00	
21	Motorcycle leg protectors				3.00	
22	Motorcycle airbags				2.00	
23	NCAP for motorcycles (NMAP)				4.00	
24	Optimised crash helmets				7.00	
25	Daytime running lights for motorcycles				3.00	
26	Pedestrian protection directive		8.00			
27	Fitment of stronger cabs and use of 3 point seatbelts					4.00
28	Improved COP on HGV load restraint	0.30				1.00

**Total Potential % Reduction in KSI by  
2010 for each user group**

**40.21      20.10      2.90      22.15      11.70**

# Italy

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**Claudio Lomonaco**  
Ministry of Transport

## ABSTRACT

This paper will provide an overview of the progress of the Italian government in the field of road safety. It reports the present Italian situation and the strategy to cope with specific issues of the country and to rules that are acted by the new European Union frameworks. At this aim the topic has been focused on three main road safety actors that are: man, vehicle and infrastructures.

## INTRODUCTION

It is necessary to have at least a concise account of the general conditions to really understand what happened in Italy during the last three years as far as safety is concerned.

Italy has roughly 57.5 million inhabitants, 38 millions of which have a driving licence.

Italian vehicle fleet consist of 31 millions of which are passenger cars, 3 million of commercial vehicles, 2.5 millions of motorcycles and 6.650 millions of mopeds. The Italian road network has a global length of 6,500 km as far as motorways are concerned, and the total length of the other roads is of about 312,000 km.

This network due to the Italian orography is affected by an important amount of mountain tracks.

**Competencies in Traffic matters.** - The main Ministries of the Italian Government involved in this complex matter are:

The Ministry of Transport, which has competencies on vehicles and drivers.

The Ministry of Public Works, whose competence covers the infrastructures;

The Ministry of Environment that is competent for the various aspects of Traffic and motor vehicles affecting the ecosystem.

I am an official of the Ministry of Transport, responsible of the Department concerning the Regulation related to the construction of motor vehicles.

## STATE OF THE PROGRESS IN ROAD SAFETY

Considering the three main subjects of the road Traffic: The man, the vehicle and the infrastructures,

we will point out the prominent phenomena, the present trends in the many fields and the most recent initiatives in progress in my country aiming at improving Traffic safety.

## The Man

**Driving licence** - The road users' fitness to drive motor vehicles can be told to be the point of top interest. The European Union has issued a Directive harmonising both driving licenses and their issuance conditions, including judgement criteria about capacities and psycho-physical conditions of the applicant.

a) **Disabled people driving.** - An aspect that had an interesting development in Italy is the one concerning vehicle driving of disabled. The EEC Directive on driving licences establishes the main criteria to determine whether the applicant, although disabled, has nonetheless the fitness requisites to obtain a "special" driving licence. In Italy most part of these criteria were inserted into our Traffic Code and in parallel many activities have been started to improve the mobility of disabled people in the recent past. In fact an important project to implement specialised Centres, where the residual abilities of disabled are evaluated, has made it possible, also through a fruitful co-operation with motor vehicle manufacturers, the establishment of a process to remove "bureaucratic" and "practical" barriers that have been limiting so far the mobility of disabled.

This project is already in an advanced phase of development in Italy, while it has been started in other European and extra-European countries. In Italy 11 Centres were built in the main areas of the country. At these sites disabled are visited by a specialised medical staff and are given a global report on their residual capabilities to use vehicle driving devices. This is accomplished by means of a test rig simulating driving conditions, whose data are sent to a computerised equipment. Moreover disabled may try driving on an adapted vehicle, thus acquiring a comprehensive view of the possibilities to recover mobility.

This project was so appreciated that the E.U. Commission DG VII asked for the involvement of the manufacturer's experience in the INCA initiative (Inventory of the European legislation and regulations for Car Adaptation), which is a study of mobility problems of disabled in Europe.

This study has been consolidated by establishing a specific group, constituted by people from Organisations involved in disabled mobility in some European Union countries (CARA for Belgium, CBR for Netherlands and Mobility Unit for United Kingdom), from test laboratories (TRL for United Kingdom, TUV for Germany and TNO for Netherlands) and from car manufacturers (Fiat Auto for Italy).

The INCA Group has firstly the scope to supply a scenario of law requirements on driving license granting and on the approval of adapted vehicles to be driven by disabled. In addition the Group will prepare, at the end of its work, some guidelines to enable the EU Commission to start harmonised initiatives within the European Union to the aim at improving mobility of "European disabled" within a frame of Traffic safety addressed to all European citizens without discriminations.

b) Young people driving - Inexperience and rush are two of the most prominent characteristics of youths who are mainly involved in severe car accidents with respects to older drivers.

In order to limit this hazard several actions are possible.

The first one concerns the conditions that involve the new driver in the first spell.

Generally speaking, in Europe the driver may drive only after the driving license delivery. Namely after twenty hours of driving lectures, which of course can offer a very limited driving experience.

In Italy and UK the candidate to the driving licence gets a temporary driving permission after a preliminary examination, which qualifies him to drive on condition to have on his side an experienced driver. The good results come out by the Italian and British experience have leaded the French govern to introduce the "guided driving". This action allows the youths to drive at sixteen years old in company with an expertise driver and to have attended the theory lectures by a driving school.

Statistical data demonstrate that the first spell of two years, after the obtaining of the driving licence, are the most dangerous. In order to prevent this situation the formation of very young people and children, finalised to an increased road safety, is relevant. First of all because it could avoid a huge part of accidents where very young people and children are involved. Secondly it is an indirect tool to shape the mentality of future adults in order to prepare them to the future responsibility as drivers and road users.

For the above reasons, the road safety is part of school teaching programmes in overall European countries nowadays.

Anyway, the regularity and the quality of these programmes, even their existence, are extremely dishomogeneous from country to country and also from school to school in the same member state.

One of the possible way to cope this situation could be to introduce exams to the release the driving licence also for mopeds. Such action has been already adopted successfully by France.

c) Saturday night accidents - A phenomenon which is becoming relevant and touching the public interest, cause the social repercussions, is the Saturday night accidentology.

Such terminology is used to point out the high number of road accidents, which come out from Saturday nights. They are caused, frequently, by the exit of youths from discotheques.

Fatalities reach the highest level within the Saturday night time zone since 24 until 5 in the Sunday morning.

Such time zone has been cited several time into the legislative proposal aimed to reduce the opening hours of the discotheques.

Actually, it has been demonstrated that the 63.5 % of young people involved in accident were moving for fun.

It has to be noted that Saturday nights accidents involve mainly male drivers which have an age within 19 and 25. The 34% of accidents involve young drivers with the driving licence obtained since one year before.

Another factor which increases the number of casualties is the behaviour to drive in company of many people (in a lot of cases they are too many). The average of people recorded in each crashed car is 2.8 people.

The driving under alcohol or drug effect is not a secondary aspect of Saturday night accidents.

The present Italian legislation does not allow to record clues concerning the psycho-physical state of drivers involved in severe accidents, such as: the alcohol rate present in the blood (TAS), the assessing of exciting state or drowsiness, derived by the assumption of drug or medicine etc.

As a consequence this leads to biased surveys which report only cases where an abnormal driver's state resulted clearly visible by the police service.

Notwithstanding, the Italian Statistical Institute (ISTAT) records 1500 severe accidents each year, caused by an abnormal psycho-physical state of the driver: drunkenness caused by alcohol, drug assumption, medicine assumption or drowsiness.

These data are probably underappraised but the first information that they imply is the high level of dangerousness caused by these factors.

Certainly in the other European countries the public attention is very sensitive about this issue. The rate of accidents caused by alcohol is relevant in all the member countries. Anyway in Italy the recorded increment of these last years lets suppose also a proportional increasing of the submerged data of the phenomenon.

As a first measure, the Italian government has increased police controls on the roads, in strict proximity of discotheques during the most critical hours.

Furthermore public information campaigns, have acted programmes and advertising messages to make road users aware about effects of alcohol and drug consumption on the driving behaviour.

Immediate low cost solutions. - Recently the Commission has presented to the European parliament several low cost proposals (less than 1 million ECU per saved life). In case of adoption by the member State, these actions could perform efficiently to cope with the Traffic safety.

Road casualties would decrease about 15 %, if the safety belts were used overall the European Union like in the Member State which really fulfil this obligation.

It would have a reduction of casualties from 5 to 40%, if authorities succeeded to oblige or convincing to quit driving when people has an alcohol rate higher than 0.5 g/l.

Road victims would decrease over 16% if drivers did not drive under drug or medicine effect.

It is also advisable, that public information campaigns would be acted to educate and to improve the knowledge of a proper consumption of alcohol related to the limits fixed by the law.

### **The vehicle**

As far as the vehicle is concerned, I think that the most meaningful news are concentrated on the harmonisation work in progress in Europe to entirely accomplish the European Union, in terms of type approval procedures of motor vehicles. In January 1998 the mandatory harmonisation process for passenger cars was completed : the type approval is now granted by applying the same procedure in all E.U. Countries.

Within the law requirements established by the E.U. in the last length of time we may recall the endorsement of frontal and side impact tests, based on biomechanical criteria, a series of more stringent requirements on the installation of safety belts in motor vehicles, particularly small buses. In addition, in the field of active safety new Directives on braking and on the installation of lighting

and light-signalling devices have been issued. Then it may be helpful to remind here that also the public transport was taken into consideration with the works to prepare a new Directive on bus construction. In particular also transport exigencies of disabled were accounted for, this being a very complex problem in the frame of public transport.

I would like also to draw your attention on what the UNO/ECE has at the stage of final approval three new draft Regulation concerning the safety of gas propelled vehicles:

- One for LPG

- One for CNG

- One for retrofit equipment either LPG or CNG

The Italian Delegation directly contributed drafting the last two proposals, basing them on its experience in this field, gained on a fleet of in-use CNG vehicles of about 200,000 units and a significant presence of LPG vehicles (about 1,300,000 in-use vehicles).

Another contribution, from the point of view of the renewal of the car park, was the introduction in Italy of incentives to eco-vehicles, included those equipped with gas propulsion.

The growing presence of low emission vehicles implied the urgency of harmonised requirements, even in this field, devoted, not only to new vehicles, but also to adapted in-use vehicles. This because it was interesting to reduce emissions from in-use vehicles too, making use of the mainspring of the economic advantage of LPG and natural gas with respect to traditional fuels, petrol and diesel. To make it possible, with the assurance of an installation conform to valid safety principles, it was necessary to prepare requirements tailored to the type of technology used, hence pressure systems fitted with safety devices suitable to prevent burst and fire.

### **Infrastructures.**

The basic information on this subject is that in our country the 85% of the transport of goods is carried out on roads in a mostly mountainous area and extended more in length than in width. This causes traffic jams roads and environmental problems.

The political approach to this situation is basically to transfer part of this transport to the rail network or to the Intermodale transport. This could result, in the future, in an amelioration of the critical status of the road Traffic. Contemporary the economical situation, in these last years, imposed general budget restrictions so that the main public works on the road network had consequently some important restrictions. Thus it was decided to devote the remaining efforts to improve the roads in the most critical areas (especially enlarging the main motorways and highways where it was recognised the presence of "black points").

# Japan

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**Shoji Watanabe**

Ministry of International Trade and Industry

## Introduction

My name is Shoji Watanabe and I represent the Automobile Division, Machinery and Information Industries Bureau of Japan's Ministry of International Trade and Industry. It is a tremendous honor for me to present the Status Report on Japan in behalf of the Japanese government at this international conference on automobile safety.

Today, I would like to report of the current state of automobile safety in Japan after two years, when the status report was given during the last conference held in Melbourne.

## The Status on Traffic Accidents

When the previous report was given, the number of fatalities caused by traffic accidents had exceeded the 10,000 mark. Since then, the number of accident-caused deaths has declined for two consecutive years, marking 9,640 last year, down by nearly 300 from the year before last.

Although there may be various reasons for the decline, the foremost factor probably is improvement in safety technologies, including measures taken toward automobile crashworthiness. This is followed by improvement in emergency action in case of an accident - specifically, the contribution of the paramedic who has been allowed to ride the ambulance. Furthermore, we believe that traffic safety education, improvement of traffic safety facilities, etc., that are being carried out diligently on continuing basis are slowly bearing fruit.

Let me report the status on traffic accidents.

In Japan, fatalities among youths aged between sixteen and twenty-four and elderly persons aged sixty-five or over totaled 5,178 in 1997, accounting for more than half of the total number of deaths.

In terms of circumstances of death, the largest number were car drivers or passengers, counting 4,251 or 44.1 % of all deaths. The second were pedestrians, numbering 2,643. In the breakdown by age and circumstance, the largest number were aged pedestrians who totaled 1,566. This is followed by young car drivers, numbering 1,168.

Compared to last year, there has not been any increase in the number of fatalities exceeding 100 in either breakdown by age or by circumstance. It is believed that there is no significant change in the

number of fatalities, remaining roughly constant at around 10,000. In view of the falling birth rate, the number of accidents involving youths is expected to fall in relation to other age groups. This trend is already seen in last year's traffic accident statistics. The number of fatalities among youths riding motorcycles has dropped dramatically.

In the breakdown by time of day, accidents involving fatalities account for 54.8%, or the larger part of fatalities than accidents occurring during the day. Lastly, the breakdown of fatalities by type of accident shows that vehicle-to-vehicle accidents account for 46.9%, vehicle-to-pedestrian accidents 27.8%, and accidents by single vehicle 24.7%. The three categories make up 99.4% of all fatalities.

## Traffic Accident Surveys

Surveys on traffic accidents provide basic information in assessment of circumstances involved in accidents and to developing safety measures. Without such surveys, appropriate action on traffic safety is probably not possible. In Japan, analytical studies on traffic accidents have been conducted with the establishment of the Institute for Traffic Accident Research and Data Analysis in March 1992.

In the publicity booklet the Institute publishes several times every year, findings based on accident data analyzed from various perspectives are made available nationwide, providing timely data on traffic accident trends among the elderly and relationships between vehicle models and accidents.

The Institute not only studies into macro data gathered on a national scale but engages in in-depth studies on microscopic level as well. The Tsukuba survey office has been set up in Tsukuba City in 1993 for full-scale in-depth research. The study involves gathering data items numbering in several thousands for analysis in as greater detail as possible.

## Improvement in Automobile Safety

As the technical index on automobile safety, the Council for Transport Technology submitted under commission of the Minister of Transport its third report in 1992, from which aggressive action was to be promoted in development of technologies in "accident avoidance," "damage mitigation," and "post-collision injury mitigation." These indices were defined in view

of the rising motor vehicle speed caused by development of expressway networks, growing trend toward nighttime activities, rising age of the population, and others.

In order to address issues concerning betterment and reinforcement of regulations or provisions in regulations, revision of safety regulations and "promotion of safety research" as medium - and long-range policy were announced. I would like to present the principal actions taken in these areas. Starting in April 1994, regulations were strengthened on frontal crash tests and on high-speed braking performance.

Braking requirements for trucks and buses have also been boosted. Starting in February 1996, performance requirements for head lamps has been revised partially. Automatic lighting of head lamp has become a requirement for motorcycles as well. Lateral crash tests will also become compulsory starting this October.

Currently, research is under way on information display devices such as car navigation systems, protection of pedestrians including study into frontal structure of vehicles, and other areas of improvement in automobile safety.

Next, I would like to report on the research coordination program approved at the 15th ESV International Conference. Preparations have been made in Japan last year, and action on each theme is currently under way. Since Japan has become the leader nation in pedestrian protection, we intend to contribute actively on each theme, including hosting meetings in Japan.

As part of the effort to promote automobile safety, the National Organization for Automotive Safety and Victims' Aid is offering on experimental basis automobile safety information to car users in general since 1991. The information has included names of specific motor vehicle models since 1996, and the Institute plans to work on greater improvement in data availability.

### **Advanced Technologies**

The Advanced Safety Vehicle (ASV) Plan that the Ministry of Transport executed as a five-year plan from 1991 to 1995 was able to produce a conceptual design of a safe, next-generation vehicle through production and demonstration of nineteen prototype vehicles and proposal on twenty items regarding advanced safety technology.

The second ASV Plan has started in 1996, which study is being conducted into human interface for preventive safety and accident avoidance, alignment with transportation infrastructure, etc. The new Plan

covers not only passenger cars but trucks, buses, and motorcycles as well and is expected to contribute to advancement in motor vehicle safety technologies in the coming century.

In Japan, action on Intelligent Transport Systems (ITS) has progressed with five relevant government ministries and agencies developing a general plan in July 1996. Based on this plan, efforts are being made into research for advances in navigation systems, electronic toll collection systems, safe driving technologies, etc., along with improvement in transportation infrastructure.

We are planning to announce the outline of Japan's system architecture for ITS at the next ITS World Conference in Seoul.

### **International Harmonization**

Although motor vehicle standards are believed to reflect the social climate, conditions in traffic accidents, traffic environment, and other elements in a country, we believe that international harmonization of standards must be studied in face of rapid progress in international marketing of motor vehicles in recent years and the need to ease distribution on the international level.

Therefore, Japan has just announced its plan to participate in international standardization activities at the UN European Economic Committee's Motor Vehicle Structure Group (ECE/WP29) and to join the revised 1958 UN ECE agreement, the agreement on mutual approval of motor vehicle devices, etc., through activities of the Japan Automobile Standards Internationalization Center (JASIC) established in 1987.

Although regulating motor vehicle performance is not an easy task because of the diversity of changes in automobile performance by driving conditions and other environmental factors, harmonization is essential considering that automobiles are being distributed internationally and wield great influence on transportation and economic activities. Hence, Japan plans to contribute aggressively to international harmonization.

### **Conclusion**

In concluding my report, I would like to thank the government officials of the United States and Canada for their work in organizing this conference and earnestly hope that this conference bears many important results and greater friendship among the participants.

Thank you very much for listening.



# Australia

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**Peter Makeham**

Federal Office of Road Safety

## ABSTRACT

This paper reviews Australia's involvement in reducing road trauma in both the domestic and international arena since the 15<sup>th</sup> ESV in Melbourne, Australia.

The paper will focus on the following points:

- National Road Safety Strategy
- International Harmonised Research Activities committee
- Intelligent Transport Systems
- International Harmonisation
- New Vehicle Safety Regulations

## NATIONAL ROAD SAFETY STRATEGY

The National Road Safety Strategy is the cornerstone of Australia's road safety initiative, linking as it does the policies of all major bodies in road safety. Following its collective development by these bodies, it was adopted by Australian governments. The strategy is a collegiate document which has been endorsed by 47 organisations, which include:

- Federal/State/Territory governments,
- local governments,
- health & education agencies,
- police,
- vehicle manufacturers,
- transport industries,
- motorist associations,
- insurers, and
- community groups

The principal components of the Strategy are to:

- reduce the nation's road toll to 8 deaths/100,000 population by the year 2005;

- set road safety directions and priorities for national application, introduce best road safety practice across Australia; and
- ensure road safety efforts are linked to health, education and other portfolios, and are included as a critical part of future transport and land use planning policies.

The Strategy has led to focussed national action plans. The latest of these Plans, developed in 1997, has increased the priority directed towards traffic enforcement; rural road trauma and pedestrian road safety and vehicle standards.

Federal and State Governments have agreed to focus on the key causal factors involved in the road toll. The areas being targeted include:-

- Rural & remote area factors particularly high risk behaviours such as drink driving, speeding, fatigue and non use of seatbelts (notwithstanding Australia's high overall seat belt wearing rate).
- Vehicle standards which represent world's best practice. Harmonisation with international standards in a manner which enhances Australia's road safety performance.
- Alcohol and drink driving with a high emphasis on isolating those drivers who are continuing to drive with high blood alcohol levels.
- Speed management particularly to introduction of speed zoning to reflect the relative safety of some sections of road.
- Traffic law enforcement aimed at adopting best practice and ensuring the community understand the police role as one of road safety first.

- Fatigue management including programs to simultaneously reduce risks and improve productivity in the road transport industry.
- Research & public education activities targeting the causes of fatigue.
- Young driver competencies research and on-going development of driver competency standards and their application in driver training and licence testing.

The Strategy has been successful. The road toll has been reduced by 16.4% since 1991. The 1997 road toll of 1,764 fatalities is the lowest since 1950. The first three months of 1998 has shown further improvements.

### **INTERNATIONAL HARMONISED RESEARCH ACTIVITIES**

It is now two years since the formation of the International Harmonised Research Activities (IHRA) committee at the 1996 Enhanced Safety of Vehicles Conference in Melbourne.

At that inaugural meeting, IHRA identified six priority research areas where coordinated research effort could be focused to maximise global outcomes using the limited research resources available to us. These six areas were:

- Functional equivalence
- Intelligent Transport Systems
- Advanced offset frontal crash protection
- Vehicle compatibility
- Biomechanics
- Pedestrian safety

#### **Functional Equivalence**

The USA and Australia worked together to prepare a paper to examine the functional equivalence of regulations.

Functional equivalence has considerable potential as a transitional stage to full harmonisation. It aims to provide a bridge between standards applied by different countries which provide similar levels of injury reduction even though the technical segments and test procedures may differ.

The paper sets out a methodology for assessing standards having similar objectives which could be

considered to be functionally equivalent, and therefore able to be mutually recognised. The paper was distributed widely for comment and has now been adopted by IHRA as a suggested methodology to examine functional equivalence.

#### **Advanced Offset Frontal Crash Protection**

FORS participated in the European Experimental Vehicle Committee (EEVC) Working Group 11 work on developing ECE R94/01 and notes that the test procedure has been through a comprehensive validation program for passenger vehicles. However, Australia, and other countries, wish to extend the offset frontal test procedure to other vehicle categories in the future. To achieve this, further research will be required on barrier specification and test speed. While Australia has carried out some limited testing on a modified barrier design, resource constraints limited the extent of the work.

Australia believes that further work in offset crash protection needs to be mindful of the issue of vehicle compatibility and supports the IHRA initiative to link consideration of these two matters.

#### **Vehicle Compatibility**

Vehicle compatibility is about equalising crash outcome between unequal crash partners.

Australia supports the move from self protection (minimising the injury of individual vehicles) to a wholistic approach to minimise injury outcome for the whole vehicle fleet.

Australia has done work in developing an energy absorbing truck under-run barrier that tries to address the mass and geometric mismatch in truck/car crashes.

Within Australia, government, industry and consumer groups are involved in a cooperative research program aimed at developing a computer simulation technique to optimise side impact protection to minimise injury over a range of side impact scenarios. Once proven, such a methodology can be extended to the whole vehicle to design for maximum protection in all crash types. Ultimately, this should result in vehicle designs that are optimised with vehicle compatibility in mind.

#### **Biomechanics**

In early 1998, Australia participated in a the worldwide evaluation of the new advanced frontal dummy, THOR. The results indicated that THOR was more humanlike in its responses during testing than Hybrid III. THOR appears robust and able to discriminate between changes to the restraint system design. This ability will become increasingly important as "smart" restraint systems are being developed in the near future. THOR has been evaluated by government, industry and research organisations worldwide with encouraging results. Australia would support early considerations to make THOR the globally harmonised frontal test dummy for regulatory purposes.

Much work is being done worldwide on a number of side impact test dummies. However, Australia is concerned that insufficient emphasis is being placed on converging to a single regulatory side impact dummy. Australia strongly supports the efforts of the IHRA Biomechanics WG in coordinating research towards this important goal.

Research institutes in Australia are continuing to work on establishing the mechanisms of neck (whiplash) and head injuries.

### **Pedestrian Safety**

Pedestrians account for about 20% of fatalities on Australian roads annually.

FORS is funding work at the Road Accident Research Unit at Adelaide University to examine the performance of popular Australian passenger cars to the draft EEVC pedestrian safety test procedure. This testing is part of a project to evaluate whether the draft EEVC test procedure is relevant in the Australian situation.

The Road Accident Research Unit has been investigating pedestrian crashes for many years and is continuing its work on head injury mechanisms. This research is being provided to both the IHRA and ISO working groups for consideration.

Australia supports the development of a globally harmonised standard to improve the pedestrian friendliness of vehicle front structures.

### **INTELLIGENT TRANSPORT SYSTEMS**

Australia has had an ongoing role in ITS research, on both a national and an international level.

The Federal Office of Road Safety (FORS) has a close relationship with ITS-Australia, which was established in 1992 by representatives of industry, government and academia to promote the orderly introduction of ITS technology into Australia. FORS has provided a grant to allow ITS Australia to undertake a research project on the benefits of ITS in Australia.

FORS is also involved in promoting the intermodal benefits of ITS applications through involvement in the Transport and Logistics Working Group of the Supermarket to Asia Council.

FORS has taken a lead role in the development of a coordinated national strategy on ITS in order to maximise the potential benefits from ITS, and avoid implementation problems by promoting interoperability.

APEC and the OECD are also developing strategies for the implementation of ITS for these reasons, and Australia is responsible for leading the projects in both cases.

In the APEC forum, Australia is leading a project for the Transportation Working Group. This project involves the identification of transport problems in the APEC region, and the development of a framework of standards, and a rationale for this framework, for the initial application of ITS technologies to address these problems.

The OECD project is to form the first of three elements of a strategic vision for the integrated implementation of ITS in the OECD. It examines strategies for ITS implementation. The second element is to examine the effects of ITS implementation, and the third is to assess contributing conditions for ITS development.

Australia is also involved in the development of standards relating to ITS. A Standards Australia Subcommittee, chaired by the FORS, was established in 1995 to develop Privacy Principles to apply to ITS. The principles developed by this group have since been endorsed by the Australian Transport Council and a Code of Practice for the Electronic Tolling Industry is currently being developed.

Australia is taking a lead role in many other international activities and developments concerning

ITS. For example, Australia has strong representation on the various Working Groups on the International Standards Organisation (ISO) Technical Committee on ITS. Australia is setting the pace internationally in the area of privacy protection for ITS and the principles are attracting world wide attention. A copy of the Privacy Principles has recently been forwarded to the International Standards Organisation.

## INTERNATIONAL HARMONISATION

The importance of standards harmonisation has been recognised for centuries as necessary to overcome the uncertainties of trade. As the world became more complex, recognition of standards harmonisation has become more urgent.

Benefits from standards harmonisation should not be underestimated. Gains from standards reform in APEC in all sectors has been put at \$US200 - \$US400 billion.

The work occurring in the APEC Transportation Working Group under the leadership of Australia will assist in realising the benefits for the automotive sector promised by the Bogor declaration.

The Bogor declaration made in 1994 provided the vision for APEC:

- Free and open trade and investment in the Asia-Pacific region, no later than 2010 in the case of industrialised economies and 2020 in the case of developing economies.

With agreement that standards harmonisation is an essential component to achieve this goal, APEC economies agreed on some common themes to guide this work:

- Align APEC economies' mandatory and voluntary standards with international standards.
- Achieve mutual recognition among APEC economies of conformity assessment in regulated and voluntary sectors.
- Promote cooperation in technical infrastructure development to facilitate broad participation in mutual recognition arrangements in both regulated and voluntary sectors.

Being a strong believer in international automotive standards harmonisation, Australia proposed the Road

Transport Harmonisation Project to APEC at the April 1994 meeting of the Transportation Working Group in Auckland.

The project proposed three objectives:

- Identify current arrangements for vehicle construction regulations, mutual recognition of conformity assessment and certification.
- Identify and develop strategies to provide harmonised requirements for road vehicles.
- Identify and specify national standards for road user requirements and identify strategies to provide harmonised requirements where appropriate.

The third objective was not pursued immediately. However, last year, Chinese Taipei proposed a project to take this issue further. This project has the potential to make a significant contribution to reducing the tragic road toll in the APEC region.

To achieve the objectives of vehicle standards harmonisation, the APEC Road Transport Harmonisation Project proposed five phases :

1. Survey the regulations applied in the region.
2. Pilot project to analyse a small number of passenger car design features regulated in the region.
3. Analyse the vehicle design features regulated in the region to identify commonalities and differences.
4. Examine the conformity assessment and certification arrangements utilised in APEC
5. Develop a harmonised regulatory regime

In phase 3 a consultant analysed APEC wide regulations applying to over seventy automotive design features. This provided APEC members with an improved understanding of each others automotive regulatory requirements.

In phase 4, work is being conducted during 1998 on conformity assessment, certification and recall regimes in the APEC region.

Phases 3 and 4 provide the building blocks necessary to develop a harmonised system for vehicle regulations and conformity assessment requirements in the APEC region.

Planning is now underway to reach our ultimate goal of harmonised arrangements for the APEC region. The final phase is anticipated to take five years to complete with work commencing in 1999. This will not be an easy task but with goodwill and the cooperation which has been a feature of APEC we are looking forward to meeting the challenge.

#### **Transportation Working Group's Collective Action Plan**

The first initiative was to encourage APEC members to engage in dialogue with the United Nations Economic Commission for Europe Working Party on Transport (UN/ECE WP29).

In April 1998, Australia and Mexico hosted an international road vehicle standards harmonisation seminar as part of the 13<sup>th</sup> Transportation Working Group meeting.

Representatives of government automotive regulatory agencies and major automotive industry groups from APEC member economies attended the seminar together with representatives of international motor vehicle and motor cycle manufacturers, consumer groups and the UN/ECE WP29.

The seminar achieved its objectives of raising awareness of the standards harmonisation activities of UN/ECE WP29 and developing strategies to progress the automotive standards harmonisation agenda in the APEC region. The seminar provided valuable input in determining the future direction of automotive standards harmonisation activities for the APEC Transportation Working Group.

Recognising the trade facilitation benefits achieved through automotive standards harmonisation, APEC governments were encouraged by participants to increase involvement in the activities of UN/ECE WP29 to accelerate alignment of APEC domestic automotive standards with international standards.

#### **Model Mutual Recognition Agreement**

The second important initiative of APEC Road Transport Harmonisation Project was the development of a model Mutual Recognition Arrangement for automotive product to facilitate trade in the region in the short to medium term until harmonisation has been achieved.

The model provides an agreed overarching document for use by APEC economies to establish bilateral or multilateral arrangements where signatory governments agree to ensure traded product meets the technical regulations of the recipient economy. It does not attempt to set standards or harmonise standards between the signatories but it does allow the parties to accept product with the assurance necessary that its local requirements have been complied with.

These arrangements will reduce domestic inspection requirements on imported product and increase the level of confidence in the capability of the technical infrastructure in the exporting economy.

The model mutual recognition agreement was endorsed by APEC transport ministers at their meeting in June last.

#### **NEW VEHICLE SAFETY REGULATIONS**

The Federal Office of Road Safety (FORS) has put into place Australian Design Rule 73/00 to implement UN ECE Regulation 94/01 for offset frontal crash protection. ADR 73/00 will be introduced for new passenger car model approvals from 1 January 2000.

ADR 73/00 will be introduced in addition to ADR 69/00 for full frontal impact occupant protection.

ADR 69/00 was introduced in July 1995 and is based on US Federal Motor Vehicle Safety Standard 208 with the important difference being that ADR 69/00 is a restrained only test with a perpendicular impact direction. This difference has allowed vehicle manufacturers to optimise their airbag systems for restrained occupants.

ADR 72/00 for dynamic side impact occupant protection will be introduced in January 1999 for passenger cars. This Design Rule will accept compliance with either US FMVSS 214 or ECE Regulation 95/01. Work is currently underway to extend this requirement to four wheel drives, and light commercial vehicles.

FORS has also completed a project to examine the feasibility and benefits of a harmonised side impact standard. The paper on this project will be presented this week during the conference.

#### **THE FUTURE**

As we move into the 21<sup>st</sup> century, Australia supports the IHRA initiative for coordinated research in major areas to improve road safety.

It is important that we do not lose sight of the "big picture" – of how these research areas might interact to improve both vehicle and road safety. We must be careful to ensure that improvement in one area does not degrade safety in another.

We must be mindful of the horrific road toll in developing countries. Our work in APEC is not only about trade facilitation but will also bring about significant reductions in road trauma in developing countries by making safer cars available at an affordable price.

# The Netherlands

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Gerard J.M. Meekel  
Ministry of Transport

## INTRODUCTION.

Some four years ago the Ministry of Transport, Public Works and Water-management in the Netherlands set up a working-party to look into the basis for a coherent package of measures related to vehicle policy. This package consisted of measures aimed at

- new technological developments
- enhancement of safety features and
- optimal economic use of heavy goods vehicles

The main goals for the long term are

- development and promotion of an intelligent vehicle
- promotion of hybrid propulsion

and for the short term

- continuing improvement of collision safety
- optimisation of the use of heavy goods vehicles

What was the background for this study? There are numerous improvements which can be introduced to enhance the safety of vehicles. It is more important to recognise and establish those measures which are the most promising in terms of cost/benefit, and which together constitute a coherent and logical set of measures. At the same time, steps should be taken to ensure that those measures which are not an integral part of package are not neglected.

Motor-vehicles traffic creates a micro-macro paradox. At micro-level, based upon arguments we all know well, the individual car user considers it as an ideal means of transport. However, at macro-level, the community considers it as having an adverse affect on safety and the environment, of course caused mainly by the "neighbours and all the others".

With this new vehicle-related policy, and depending upon the type of problem, one can opt for either technical changes to vehicles, alterations to pricing policy, influencing the buyer's or driver's behaviour, stimulation of public transport, or new

infrastructure. The preferred option is for measures which are of a structural nature rather than those which merely tackle symptoms.

Paying close attention to vehicle-related policy is one means of attaining goals for accessibility, enhancement of traffic safety, environmental protection, economy and energy-savings. The Ministry of Transport, Public Transport and Water-management in the Netherlands has focused its vehicle-related policy on accessibility and traffic safety, while paying requisite attention to environmental aspects. The success of any policy, including those mentioned above, is heavily dependent on sufficient support from the users and those organisations which serve the interests of the consumers, the environment, public transport, etc.

In order to be successful and attain a position from which to influence certain developments it is necessary to have available sufficient technological research centres where knowledge is developed on a national basis.

## CHOICE OF PRIORITIES.

Development of a sound vehicle-related policy depends on a several participants: consumers and vehicle manufacturers world-wide, the electronics industry, research institutes, European governments and organisations, governments in neighbour states, national and local governments in one country and different departments within one government (economic affairs, environment, finance). All these participants, including the Ministry of Transport, have their own restricted possibilities for attaining their pre-determined goals. This results in a balancing of the activities of the government, according to the constraints imposed by the available manpower and financial resources.

The question therefore arises of how to reach an optimum package of measures from the 160 measures which were evaluated. After careful evaluation of all possible measures, the most promising are considered to be those related to technical innovation, namely:

- the development of an intelligent vehicle
- the development of alternative propulsion systems, mainly the hybrid propulsion.

However, these two developments will have a noticeable effect only on a long-term basis.

At the same time the decision was made to continue with the present-day activities related to improving collision safety and optimisation of heavy goods vehicles: a great many positive results are still possible, given sufficient action and measures with regard to collision safety aspects. In addition, heavy goods vehicles are considered to have sufficient potential for enhancement of safety and environment, such as improvements in logistics, collision safety, road traffic behaviour and emissions.

One reason for these greater expectations for HGV's may well be the fact that less attention was paid to this category of vehicles in the past. A balance was to be found between short term and long term activities, as was a balance between measures related to accessibility (e.g. centres of cities), traffic safety environment, energy and economy.

#### HIGHLY POTENTIAL MEASURES.

One of the most promising activities is the realisation of a standardised set of design specifications for an electronic architecture in the car, for communication between vehicle and road, and between vehicles themselves. Opportunities relate to:

- dynamic traffic information
- intelligent speed adapters
- electronic vehicle identification
- on-board computer (e.g. OBD)
- collision avoidance systems
- autonomous intelligent cruise control
- automatic vehicle guidance systems.

Another set of promising measures relates to propulsion systems and (alternative) fuels in order to attain environmental and fuel efficiency goals. Most promising for the short term are the use of hybrid vehicles, and the use of LPG/LNG. With highly efficient small conventional combustion engines, a fuel consumption of 2-3 litres/100 km can be attained. Influencing the consumer when buying his car can also be successful with the use of, for example, tax incentives.

#### PASSIVE SAFETY.

In this area the reduction of the negative consequences of a collision has still great potential; improvements to the bodywork, safety belts, child restraints, and side-impact protection. The EURO-NCAP programme can have positive consequences to safety aspects of vehicles. However, this programme should be part of a broader scheme, preferably within the European Community, with a greater number of participants and with stricter rules concerning the application of results found during the test programmes.

#### HEAVY GOODS VEHICLES.

During the last ten years technological aspects have been improving steadily, but there is still potential for improvement in environmental aspects such as emission and noise, and fuel efficiency. Reduction of mileage by better combinations of cargo, resulting in higher loading ratios and better use of road capacity and infrastructure are other measures which yield positive results.

Heavy goods vehicles are involved in 20% of the annual 1200 road traffic fatalities.

Improvements with great potential concern the front and rear under-run protection devices and side guard. In addition, better side guards, e.g. with closed surfaces, have special potential in relation to contacts with vulnerable road users (pedestrians, cyclists) and can reduce the injuries in 35-50% of the accidents.

Another aspect is the optimisation of the maintenance of heavy goods vehicle from its first kilometre. This improves environment and reduces the overall costs for the vehicle or fleet-owner.

#### CONCLUSION

The study, which started some years ago, on the optimisation of the actions resulting from a vehicle-related policy within the Ministry of Transport, Public Works and Water-management underlined the categories of vehicles, the aspects and items which have promise with regard to enhancements in safety, environment and economy, and accessibility of e.g. city centres for the short and long term. Programmes have been running from some years. Most promising for the long term are the development of intelligent vehicles and the promotion of hybrid propulsion.

One interesting programme is the twelve-kilometre test-track for the study of automated guided vehicle systems in the Netherlands, which will be in use as from June 15, 1998.



The Ministry of Transport will continuously analyse the opportunities for enhancing safety and environmental aspects of vehicles. At the same time

it will analyse the cost/benefit aspects of these measures and optimise its input with manpower and financial sources.

## Sweden

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### ABSTRACT

A reduction of road traffic fatalities and serious injuries in Sweden started in 1990 and has continued until 1996. However, during 1997 a slight increase of fatalities was observed. The road safety work in Sweden has been stepped up during the 90ies. A new national road safety programme was presented in 1994. The Vision Zero, which was presented in 1996, was accepted by the Parliament in 1997, as the basis and long term target for the Swedish road safety work. A new national road safety programme is now under development.

On specific international topics, Sweden has been active in a project aiming at independent consumer information about car safety (EURO-NCAP), in field trials with Intelligent Speed Adaptation (ISA), in development of ISOFIX standardised anchorage for child seats and in developing intelligent belt reminders. Special national topics are quality control of road safety, a large fleet study of alcohol effectiveness and development of a safe travel policy. In the research area, in-depth studies of all fatal road accidents, studies of neck injuries in rear end crashes, roadside to vehicle crash compatibility, tire characteristics in accidents, pedestrian protection in collisions with cars and crash recorder data, could be mentioned.

### ACCIDENTS, INJURIES AND FATALITIES

The first specified Swedish road safety target, for maximum number of road traffic fatalities per year, was set to 600 when the yearly fatalities was 800 in the late 80ies. That target was reached in 1994. Then a new target was set to maximum 400 by the year 2000. We have not really got much closer to that target since then. The fatality figure 1997 was 570. That was an increase by six percent compared to 1996.

The main part of the increase in fatalities is car drivers on winter roads. Both number of seriously and slightly injured persons have increased. Only seriously injured pedestrians have decreased. The main part of the increase has happened on main roads, not in built up areas.

The passenger car covers more than 80 percent of the personal transport in the country. Two thirds of the fatalities are car occupants. 85 percent of the fatalities of car occupants occur outside built-up areas. For pedestrians and cyclists the vast majority

of fatalities occur in collisions with cars within built-up areas.

The higher the age the higher the number of killed pedestrians and cyclists. Mopedists (drivers of small motorcycles) are the only road user category for which the fatality age curve is bimodal. The tops are at age 15 and age 75. The motorcycle fatality curve has its maximum at about 25 years of age. The top of the car occupancy fatality curve is about 30 years of age. These frequency figures are of course the result of both risk and exposure.

### ROAD SAFETY POLICY

The Swedish Parliament came to a radical and very brave decision in October 1997. Then it was decided that The Vision Zero should constitute the long term target and the policy basis for road safety work in Sweden. That means that the ambition will be the same in road transport as it is for instance in flight transport and in rail transport – nobody should be killed or seriously impaired.

Not everybody realises how radical this decision is. In fact it means an almost total change of policy. Earlier we accepted the safety we could get when the transport and mobility requirements were fulfilled. What the Swedish Parliament is now saying is that we will have the mobility and transport efficiency that our safety requirements permit.

A proposal put forward by the government is that the short term road safety target is to reduce the number of road traffic fatalities to not more than 300 by the year 2007. That is a reduction of almost 50 percent from the 1996 figures. That would mean less than 2.8 fatalities per 100.000 inhabitants. The present figure is almost twice as high. A road safety programme for the years 1999-2007 is now being developed.

As usual road safety work may be carried out along three axes:

- Reduce exposure
- Reduce accident risk
- Reduce crash consequence

It is the product of the achievement in each one of these three axes that decide the results.

Historically we have worked intensively to reduce accident risk. The results have however not quite reached our targets. One of the reasons is the

compensatory behaviour of the drivers. In the last decades we have worked quite successfully to reduce crash consequence. We have so far not really systematically worked to reduce traffic exposure. The strong pressure along that axis comes today from the environmentalists. We should join our forces.

Acceptance of the Zero Fatality Vision as the basis for our road safety work means a change of gravity from accident prevention measures to reduced crash consequence and exposure measures. There are a number of possibilities to achieve reduced consequences of a crash:

- reduced violence in car and along road in case of a crash (e.g. car fronts and sides, motor ways, obstacles along the road, crash barriers, poles)
- improved personal protection of road users (e.g. belts, helmets)
- reduced speeds
- improved rescue, treatment and rehabilitation

Road improvements and to some extent car improvements have the advantage that they may improve safety at the same time as mobility, transport efficiency and environment. On the other hand they have the disadvantage that they cost money. Unfortunately the government did not decide to invest in road improvements. Therefore most of the efforts so far are concentrated on speed reduction.

## STRATEGY

Traditionally the government instrument to improve road safety in general and vehicle safety in particular has been by regulations. This instrument has, however, a serious disadvantage. It is slow:

- Regulations do not represent the most recent knowledge. It takes time to agree on regulations and they are therefore based on old knowledge. You could even say that they normally are obsolete when they are published.
- Regulations do not make full advantage of existing knowledge. Regulations are often compromises, in which the slow and/or weak party has considerable power to reduce its potential impact.

However, we no doubt need regulations to set the minimum requirements. But we should use other instruments to complement regulations and to speed up the process of safety improvement. One such complimentary method is consumer information. The modern educated consumer is a very powerful and quick actor. There are many examples of quick consumer actions in the vehicle market that have completely changed the situations.

Consumer information may however, only be fully used on some conditions:

- The information must be impartial
- The information must be up-to-date
- The information must be realistic
- The information must be accurate
- The information must be comparable
- The information must be fairly complete

Probably the most important is to agree on a test method. We think a good example of consumer safety information is the EURO-NCAP, a joint European crash test of the most common European cars of different size. Many countries carry out car safety assessment. In a joint effort Sweden, UK, a number of motoring and consumer organisations and EU carried out crash tests during 1997 and 1998 on front impact, side impact and pedestrian impact. The results are published and widely distributed. The test should be expanded because it is still far from complete. We believe the results will have quick and considerable impact on consumer behaviour and if so also on manufacturer behaviour.

One major road safety problem for authorities has always been to influence the behaviour of road users, primarily drivers. In an effort to get around that problem the Swedish Road Administration is now trying to convince commercial companies, communities and authorities that they shall require certain safety features when they buy transport.

The idea is that just as well as today more and more companies guarantee that they fulfil certain environmental requirements, they should certify that they fulfil certain road safety requirements. Such requirements might be:

- following the regulations including speed limits
- using well trained and experienced drivers
- having and wearing seat belts
- checking brakes, tires, lighting and other vehicle safety features

Filling the specified safety requirements should be a condition for participating in the tender for contract in passenger transport as well as goods transport. This way safety will be a competition variable for the transport companies. Furthermore the transport companies must certify that their drivers behave safely. Safe driver behaviour will be quality controlled not primarily by the government (the police) but by the transport companies themselves. Today professional drivers behave fairly aggressive and are in those terms often a bad model for other drivers. With company responsibility the professional driver should really be a good safety model for private drivers.

## SPECIFIC PROBLEMS

It is widely realised that speed, alcohol, belt usage and travel modes are directly or indirectly major road safety problems. During the last years we have made some efforts to reduce these problems.

Some large scale field trials of intelligent speed adaptation (ISA), or even implementation studies, are in preparation in Sweden. The purpose is to develop a speed adaptation system primarily for society financed transports, but possible to use also for other transports. The Swedish Road Administration, the communities and the car industry direct the project. Four communities serve as trial areas.

The idea is that the 40 largest towns in Sweden will be equipped with infrastructure for intelligent speed adaptation by the year 2020. This will be used by about 80 percent of the local transports and of course indirectly influence the speed of the remaining transports. On rural roads and motorways the speed adaptation will be mainly vehicle born (e.g. adaptive cruise control).

By these means it will be possible to make speed limits flexible in many ways (e.g. weather, work zones). By the year 2010 most cars will be possible to equipped for ISA. By the year 2020, 95 percent of the cars will be equipped. Initially the system will be used on a voluntary basis. But there are several possibilities to extend that – e.g. to require notorious speeders to be equipped as an alternative to withdrawing their license.

The alco-lock system senses the alcohol content in the expiration of the driver. The car will only be possible to start and to drive if this alcohol level is not exceeding a set value. The system has been tried e.g. in Australia and in Canada. Presently a large scale trial is in preparation in two Swedish counties. The idea is that drivers, who have had their license withdrawn because they have been sentenced for driving under the influence of alcohol will have the possibility to continue driving if they participate in a rehabilitation programme and equip their car with an alco-lock system.

Withdrawing the license is a common penalty for various traffic crimes (see speed and alcohol above). However, because the probability of getting caught not wearing a license is very small many drivers continue driving in spite of not having any license. Therefore withdrawing the license is not a very effective measure. One way of making it effective is to make the license electronic and make it impossible to start the car without the valid electronic license. A programme to develop an

effective electronic driver's license is in progress in Sweden since a few years.

The Swedish Road Administration has developed a policy for safe travelling of its employees, partly to increase safe and environmentally sound travelling, partly to support the market for safe and environmentally friendly cars. Many other administrations and commercial companies have also adopted this policy.

One intention with the travel policy is to reduce travelling by car. But the interesting part here, are the requirements specified on a rental or private car to be used in duty by an employee. The following requirements are valid from January 1, 1999:

- weight in working order above 1000 kg
- three point belts on seats used
- winter tires in winter conditions
- fulfil 1989 exhaust requirements
- air bag for driver (from the year 2000)

Sweden has also played a key role in the development of the ISOFIX concept, a standardised attachment for child seats. Since last autumn ISOFIX is factory installed in some European cars and we expect many other vehicle manufacturers to follow.

Until now development of roadside safety features has been somewhat different in Europe and USA. Sweden has tried to act as a co-ordinator with the purpose to improve world-wide harmonisation in this area.

Earlier studies have shown that the wearing rate of seat belts is high in general but low in severe accidents. Only about 50 percent of those car occupants that get severely injured are wearing their belts. Only in Europe 5.000 lives could be saved if all car occupants were belted. Therefore a Swedish project has put forward specifications for an inter-lock system that will put strong pressure on the occupants to wear their belts.

## RESEARCH

One car company (Volvo) and one insurance company (Folksam) have published interesting results from real world crashes recorded by in-vehicle-crash recorders. This gives a new dimension to in-depth studies.

As one of the few countries in the world Sweden is from January 1, 1997 analysing in-depth all fatal accidents in road traffic. This project has three purposes:

- follow up of the road safety situation
- awareness and education of staff
- basis for new research and modified actions

Some of the questions to answer in the present in-depth studies are:

- How many lives could have been saved by safer cars?
- Were seat belts used and if so how?
- Are roll over accident dangerous for belted occupants?
- Which were the speeds in collisions between cars and pedestrians?
- Which effects do bicycle helmets have?

The research programme of the Swedish Road Administration is split into five parts:

- evaluation of safety systems and measures
- injury data and biomechanics
- traffic medicine and traffic psychology
- decision and implementation processes
- interaction between safety and other society and transport goals

One previously overlooked research area that many researchers in Sweden from government to industry are now working with, is the whiplash neck injuries. It is a fairly frequent and treacherous injury, which is often not noticed immediately after the crash but may lead to life-long impairment.

Chalmers University in Gothenburg is one of the main research groups within the crash area. They have carried out a number of studies of the human body characteristics in crashes. One series of studies present results, which improves the understanding of brain injury. Another series deal with a mathematical model of the pedestrian body at impact with a car. A third series tries to analyse the relative significance of car mass, structure, stiffness and geometry in vehicle to vehicle frontal crashes.

The Swedish Road & Transport Research Institute (VTI) is another main research facility. By means of their advanced driving simulator they have carried out a number of studies of the safety effect of in-vehicle informatics. They have also studied accident risks in relation to type of tire used and the injury consequences for pedestrians and bicyclists. The crash laboratory has specialised on child protection and road side equipment.

The Swedish automobile manufacturers Saab and Volvo are among the leading car makes from safety point of view. This position is based on targeted research efforts. Also the insurance companies in Sweden contribute to road safety research in various aspects.

## CONCLUDING REMARKS

The Vision Zero is now widely accepted in Sweden from politicians to the drivers. It has now started to be used as a generator for new countermeasure and research ideas. The start looks promising. But it remains to be seen if it will be as successful as a basis for action and research as it has been as an inspiration source for road safety work and road safety workers.

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### ABSTRACT

The following report contains information on the progress achieved in Poland with regard to road traffic safety. At two last ESV Conferences our approach to the road accident casual factors related to vehicle and human behaviour had been presented. This time it will be discussed third of the main factors - the road. Additionally the information on progress made during last few years in scope of two other factors is also given.

### ROADS AND TRAFFIC SAFETY IN POLAND IN THE POLITICAL SYSTEM TRANSITION PERIOD

#### General description

The human behaviour at the end of 20<sup>th</sup> century is not always rational. The very significant example of the situation is implicit demand of society in many countries to largely use motor vehicles without taking into account the bad experience noticed in developed countries. The natural consequence of rapid growth of motorization is the necessity of harmonised development of road infrastructure. Unfortunately people first buy vehicles and come to the idea of building the good roads for these vehicles far too late, where both the traffic safety and mobility of vehicles are insistently threaten. The social costs of such behaviour are horrific both with regard to numbers of people involved in road accidents and the sorrow consequence of the accidents. In Poland, in three years 1994-1996 20,000 people were killed and 206,000 were injured. The deaths ratio per hundred accidents was around 11, giving us one of highest results in Europe. The accident data are widely known to the public but it does not stop people to progress in motorization. In response, the authorities in many countries look for effective measures for limiting the negative influence of dense road traffic.

World automobile industry is in majority in private hands and financed by buyers directly through vehicle price, while road construction mostly is paid through state budget, what causes much more easier control of vehicle related safety factors, than factors related to road, especially in countries during transition in which the problem of „short cover” exists in great extent.

The term „road traffic safety” has the scope limited by definition to the incidents on the road and includes also

participation of road infrastructure. By now our accident survey results in estimated 10% of total accidents number in Poland, but some experts think the value is lowered specifically with regard to the deal of deaths and serious injuries. It is evident by simple comparison that our roads have been in very poor state (ruts, pits and bumps etc.) during last 10 years, mostly due to very low budget resources for road maintenance.

The total length of road net in Poland is now around 375 thousands kilometres among which there is 46,000 kilometres have the status of main roads called "national roads". In this specific road category:

- 28 % is in state classified as "bad",
- 44 % is in state classified as "warning",
- 28 % is in good or acceptable state.

The first sign of progress in the situation occurred at the beginning of 1998 when 30% of annual fuel excise tax has been devoted by authority for road purpose. Experts say that such level of financing enables only to break further depreciation and repair the worst part of "national roads". It does not, however, allow for new investment in road infrastructure including the transit motorways. Poor finance state is also seen in lack of building the road bypass of the build up areas and modern traffic control (telematics). It is estimated that if the part of annual fuel excise tax for the road reaches 50% the most urgent needs may be satisfied.

As in all aspects of traffic safety the activity must be organised in legal and technical systems. In our way to become the member of European Union we had already published two important ordinances unifying our road and bridge technical specifications for construction and maintenance to EU standards. The road construction survey research shows that large part of existing Polish roads does not meet the EU standards, so there is a need for reconstruction of old and building new roads at least on transit directions. The legal status of responsibility of road authority in our country has to change to direct responsibility in the case of accidents clearly connected to road weak state. The vehicle insurance companies are successfully lobbying in the above mentioned field. We hope that complex activity will lead us to the level of road depending traffic safety comparable to the average EU result in few years time.

## The need for modern roads

Poland due to the geographic position in central Europe is a typical transit country (the annual transit rate of motor vehicles exceeds 27 mln) in the North-South and East-West directions and thus should make use of this advantage in its economy. For this activity there is a necessity to apply adequate network of transport measures, that means motorways and express roads the standard of which should conform to the EU. In practice, that means the roads enabling per axle loads of 115 kN. Our road network is nowadays mostly not yet prepared for such loads.

Accordingly to latest plans, the possibility to fulfil this condition will be achieved provided that:

- motorways A-1, A-2, A-3, A-4/A-12 and A-8 of the total length of 2569 kilometres will be built,
- the additional network of 2300 national roads will be rebuilt or modified for the higher axle loads.

The estimated costs of the exercise should be on the level observed in other developed countries and should not be lower than in the table below:

No.	Country	Year	The share of road expenses in relation to road taxes
1	Japan	1990	148%
2	Germany	1987	100%
3	Norway	1989	98%
4	Austria	1986	99%
5	USA	1989	83%
6	Switzerland	1988	79%
7	Belgium	1986	70%
8	Denmark	1989	33%
9	Sweden	1989	33%
10	Spain	1989	23%
11	England	1989	23%
12	Poland	1995	14%

According to „Sector study of road building enterprises and the base industry. Final synthesis”, Road and Bridge Research Institute (IBDiM), Warsaw 1997.

Despite very hard situation in road building sector in Poland, our road building companies are watching the world technology progress and could well compete in the scope of bituminous pavements. Many of them use modern technologies which allow the necessary strength of pavements fulfilling the latest EU standards to be built. With regard to the road signs, there is a substantial progress mainly in both vertical and horizontal road signs where good retroreflective paints are widely used.

In recapitulation it is worth stressing that the only reason of poor state of our roads is the lack of resources remedy this problems.

## THE PROGRESS IN THE FIELD OF VEHICLE SAFETY

In fulfilling of European Treaty further adaptation of Polish law is consequently implemented. The new Road Traffic Code more precisely defines the type approval system and periodic technical inspection system. Five EU directives have been implemented into new MoT ordinance and many others are equivalent requirements to the UN ECE 1958 Agreement Regulations used in the type approval system. The necessary documentation and layout of documents had been unified according to the European Whole Vehicle Type Approval system. Moreover, our country takes part, at its best effort, in the international initiative called International Harmonised Research Activity - IHRA about which you will hear a lot during this event.

## THE PROGRESS IN THE FIELD OF HUMAN FACTOR

Previously mentioned the new Road Traffic Code forced the centrally manned database of drivers and their faults, thus enabling better supervision of drivers behaviour on the roads. Driving license categories are now identical to EU system and a new driver training scheme is also unified to the system existing in developed countries.

## CONCLUSION

Despite all our effort, the road safety level in Poland is still not satisfactory. Taking into account the rapid growth of our car market which is now estimate on the level of more than 0.5 mln. of new vehicle and 150,000 of imported second-hand vehicle a year, it appears necessary to pay greater attention to the problem of safety on the roads. We hope that our presence on ESV and IHRA will help in better and more effective progress in the field.

I wish everybody a good co-operation and fruitful exchange of knowledge in this very important part of everyday life - road traffic safety.

## United States

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The National Highway Traffic Safety Administration (NHTSA) is challenged to initiate research and generate ideas to ensure that critical motor vehicle research continues well into the next century. It is often a slow process, but one that is critical to maintaining the pursuit of a safe and secure transportation system. The prospect of making transportation safer, laying the foundation for saving lives and reducing injuries through research, is a formidable one, and one that merits our best efforts. The following pages report NHTSA's progress and achievements that have taken place toward these goals since the last ESV conference, and over the longer term.

### CRASH ENVIRONMENT

Last year, the U.S. Department of Transportation celebrated its 30<sup>th</sup> anniversary. At times like these, it often pays dividends to retrace the path we've traveled to arrive at where we are today.

NHTSA's National Center for Statistics and Analysis (NCSA) reports that from 1992 (the lowest fatality toll for over 30 years) to 1997 (preliminary estimates), deaths on US highways increased from 39,250 to an estimated 42,000. This fatality increase has been associated, in large measure, with an expanding economy and increases in exposure. When contrasted with the 50,894 people who were killed in traffic crashes in 1966, we have seen a 17 percent decline in 30 years.

The fatality rate per 100 million vehicle miles traveled in 1966 was 5.5 (see Figure 1). By 1992, the rate had declined to 1.7, and it has remained at this level through 1997. Of course, the fatality rate decline was not a straight line downward. Rather, there have been periods of little change over the years, such as 1974-1980, 1983-1986, and of course, 1992-1997. However, we believe we are on the verge of breaking through the current barrier, and will be reporting a 1.6 fatality rate around the year 2000. Similarly, the fatality rate per 100,000 population decreased from

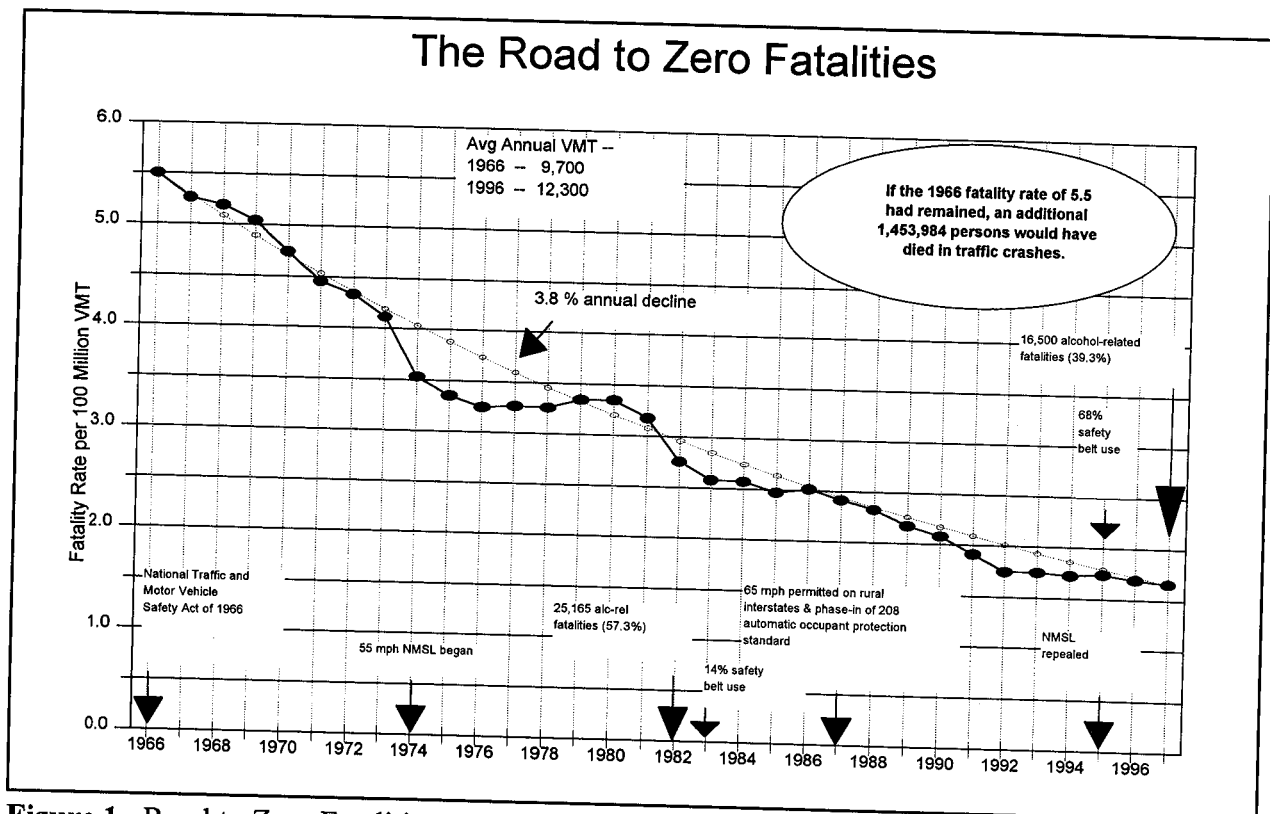


Figure 1. Road to Zero Fatalities.



26.02 in 1966 to 15.80 in 1996.

Between 1966 and 1997, the amount of travel on US roadways increased by approximately 170 percent. When compared to the 17 percent decline in fatalities, we must be doing something right! That something is saving lives. Saving lives, to the tune of 1,453,984 through 1997. That's how many more people would have lost their lives if the 1966 fatality rate of 5.5 per hundred million vehicle miles had persisted through 1997.

Passenger car occupant fatalities comprised 53 percent of the total in 1997, and continue to constitute the largest proportion of U.S. traffic fatalities. Light truck fatalities in 1997 were 24.7 percent of total fatalities, an increase from 20.6 percent in 1992. Motorcyclist fatalities in 1997 were 5.0 percent of total fatalities, a decline from 6.1 percent in 1992. Nonoccupant fatalities in 1997 were 14.5 percent of total fatalities, down from 16.2 percent in 1992.

The total number of police-reported crashes in the United States in 1997 was estimated by the National Automotive Sampling System (NASS) General Estimates System (GES) to be 6.753 million, an increase of 13 percent from the 6 million reported in 1992.

Since 1992, traffic fatalities, and the fatality rate, have varied within a relatively small range. A cursory look might give one the impression that we are now in a fairly static period. However, nothing could be further from the truth. There are a number of dynamics at play that are changing the fatality picture. Two of the more dominating factors: changes in the composition of the on-road fleet, and changes in the composition of drivers of this changing fleet.

In 1975, when the Fatality Analysis Reporting System (FARS) began collecting fatal crash information, light trucks (pickup trucks, vans and utility vehicles) accounted for about 18 percent of the on-road light vehicle fleet, about 17 percent of light vehicle VMT, and about 16 percent of light vehicle occupant fatalities. By 1996, the light truck portion had swelled to 34 percent of the on-road light vehicle fleet, 34 percent of light vehicle VMT, and 31 percent of light vehicle occupant fatalities. While passenger car occupant fatalities declined by 3,699 (14 percent), light truck occupant fatalities more than doubled, from 4,856 in 1975 to 10,360 in 1997 (an increase of 5,504, or 113 percent).

This shifting of the purchasing preference of Americans from cars to light trucks is a socio-economic trend, driven by consumer preferences. However, light

trucks are designed differently than cars, and perform differently. These differences present certain safety-related challenges. For example, it is well established that light trucks are more prone to rolling over in a crash than are passenger cars. Rollover crashes are second only to head-on crashes in their injury potential. In addition, the likelihood of an injurious occupant ejection is greatest in rollover crashes.

Perhaps at least as important is the interaction between cars and light trucks in roadway crashes. As the population of light trucks has increased from 18 percent to 34 percent, collisions between cars and light trucks have become more and more likely. In 1995, for the first time, more passenger car occupant fatalities occurred in collisions with a light truck, than occurred in collisions with another passenger car.

In 1975, 7,371 passenger car occupants died in collisions with another car, while 2,163 died in collisions with a light truck. By 1996, this picture had changed dramatically, with 4,192 passenger car occupant fatalities in collisions with another car, and 4,417 in collisions with a light truck.

An evolutionary trend to which attention should be drawn concerns the composition of the driver population. For quite some time, but especially since the early 1980's, women have increased their driver licensure at a greater rate than men. This change is even more pronounced for women age 60 years and older. Between 1975 and 1990, growth in the number of female licensed drivers outpaced males by 12.6 percent.

In addition to the increase in licensure, the average annual travel for female drivers also has increased dramatically compared to male drivers. Between 1975 and 1990, average annual miles driven by female drivers increased more than the growth in male driving by 23.7 percent. Taken together with the increase in driver licensing, the total exposure of female drivers increased 39.2 percent more than male driver exposure.

The combination of these two trends has brought about dramatic increases in female driver fatalities. Between 1975 and 1990, see Figure 2 for these trends, male driver fatalities declined by 1.3 percent, while female driver fatalities increased by 62.4 percent. Taken together, female driver fatalities have increased by 65 percent relative to male driver fatalities. These trends have continued through 1997, to the point where the increase in female driver fatalities since 1975 is now 98 percent relative to males. These trends are presented in the graph.

The 1992 report concluded that most of this increase is due to increased licensure rates and increased average annual travel, both leading to increased exposure to risk. However, even after accounting for increased exposure, there was a residual 18.2 percent increase in the fatality rate per mile traveled. This increase has been investigated, but no strong patterns have yet been identified to explain this increased risk. The growth in female driver fatalities is another trend that is expected to continue, as more women enter the workplace, life expectancy increases, and women continue to outlive men.

There continues to be other important issues that require research investments, such as air bags, antilock brakes, intelligent vehicle systems, higher speed limits, and the like. We must continue to be vigilant and monitor the changing traffic safety system. None of these problem identification activities would be possible without a solid basis of data collection, information and analysis.

## DATA COLLECTION AND ANALYSIS

NCSA has been conducting motor vehicle crash data collection for the agency since 1972. In recent years, several important changes have been made to the agency's data collection programs which will benefit not only NHTSA, but the highway safety research community, nationally and internationally.

NHTSA's crash data collection system is composed of several components serving various needs. The Fatality Analysis Reporting System (FARS), which began operation in 1975, is a census of all fatal crashes occurring on public roads in the United States. The National Automotive Sampling System (NASS) is a yearly collection of data from a statistically representative sample of crashes occurring in the United States. NHTSA implemented the first full year of NASS data collection in January of 1979. The program was re-evaluated in the mid-1980's, which resulted in a redirection of the program focusing on vehicle crash protection performance and created a two component NASS system which was implemented in January 1988. The two components are the General Estimates System (GES) and the Crashworthiness Data System (CDS). FARS and NASS are complemented by state crash data files compiled from police traffic crash reports for a number of states.

FARS data has been used to assess the effectiveness of numerous programs, including those that increase seat belt use to evaluate the performance of various occupant restraint systems, including air bags. In 1997, FARS data was made available for analysis on the World Wide Web through the Internet.

In 1995, additional detailed information on air bag performance was added to the NASS CDS. Collection of precrash environmental data in support of the Intelligent Transportation System (ITS) was added to the NASS CDS and GES. The NASS CDS sampling plan was modified in 1996 to increase the number of crashes involving air bag-equipped vehicles in support of the agency's evaluation of air bag system performance and regulatory initiatives. In the summer of 1995, a Pedestrian Crash Data Study was implemented in NASS CDS to update pedestrian injury patterns in impacts with late model year passenger vehicles. In the spring of 1996, a 2-year Unsafe Driver Actions Special Study was implemented in NASS CDS to identify specific action(s) taken by the driver of the vehicle that initiated the crash sequence and further identify the cause of that action.

Since 1972, NHTSA's Special Crash Investigations (SCI) program has provided us with the most in-depth and detailed level of crash investigation data collected by the Agency. The program provides NHTSA with the flexibility to acquire detailed engineering information on crashes of special interest that fall outside the established scope or criteria of other agency data collection systems, for examining the real-world safety impact of rapidly changing technology and exploring alleged vehicle defects. These include but are not limited to investigation of crashes in which an air bag or safety belt system appeared to operate in an unexpected manner, crashes involving alternative fuel vehicles, crashes involving children in restraints, and serious school bus crashes not investigated by other Federal agencies.

As new highway safety issues emerge, the Special Crash Investigations program has the capability to respond quickly for collection of field information to support NHTSA's analysis and appropriate action. Crash data from this program is used to produce monthly reports on fatal and seriously injured children and adults in air bag deployment related crashes.

The objective of the State Data Program is to obtain motor vehicle traffic data files from select states and process those files into databases usable by NHTSA analysts. Each year, the crash data files from 17 states are obtained documented and converted into Statistical Analysis System (SAS) format. Additionally, a specialized crashworthiness database is created from several of the raw state data files. State data files have been used in studies of driver error, antilock braking systems, and center high mounted stop lights, among others.

Through the State Data Program, NHTSA continues to encourage states to improve the usability of their data for highway safety analysis. State crash

data are used at the state level to perform problem identification, establish goals and performance measures, determine progress of specific programs, and support the development and evaluation of highway and vehicle safety countermeasures. Standardization of state data can help to ensure the success of these efforts. Comparable information more accurately identifies where resources could be applied among important programs, provides for better performance measures, and supports evaluation of effectiveness of programs. Standardized data elements facilitate linkage to medical outcome data, thereby helping identify the cost of traffic crashes and, ultimately, who pays. At the National level, comparable state data improve NHTSA and the Federal Highway Administration (FHWA) analyses and the collection and coding of information in Federal data systems, most of which also are used by state and local agencies.

In another component of the State Data Program, NHTSA continues to work with states to develop Crash Outcome Data Evaluation Systems (CODES). CODES links occupant-specific statewide police-reported crash data to medical outcome data, information collected by emergency medical services, emergency departments, hospitals, rehabilitation, and long term care centers, and to other traffic records. These linked data can be used to determine the person, crash, vehicle and roadway characteristics that are most associated with increased injury severity and high health care costs. With this information, priorities can be set that will have the most impact on reducing mortality, morbidity and costs.

The primary component of the CODES program is to provide seed funding for states to begin linking data. In 1997, grants were provided to seven new states to develop CODES, bringing the total to 16 states that have been funded to develop CODES data linkage capabilities or to develop applications for their linked data. Six of the original seven states provide peer-to-peer technical assistance to other states interested in or actually developing a CODES. In 1998, up to six more states will receive CODES grants.

Linked crash and injury databases are a crucial source of medical and financial outcome information for motor vehicle crashes. Unfortunately, not all states are currently able to develop data linkage capabilities. For linkage to occur, states must have computerized, population-based data. Most states have crash and hospital discharge data. Many states are in the process of developing computerized systems for emergency medical services, emergency department and other outpatient data. To facilitate this development, NHTSA, in partnership with the Centers for Disease Control (CDC) and other Federal agencies and national

organizations, supports national efforts to standardize these data.

## **CRASH AVOIDANCE RESEARCH**

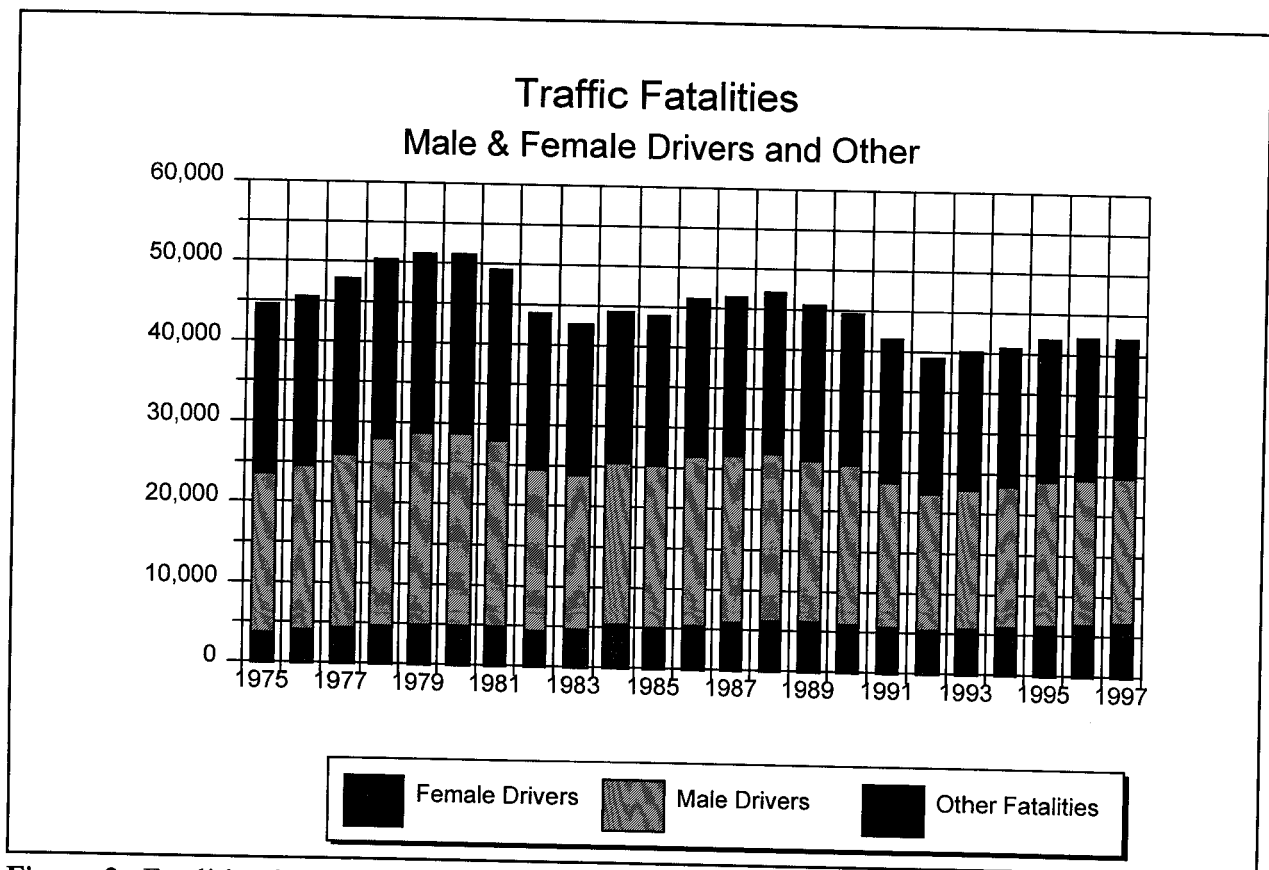
### **Intelligent Transportation Systems (ITS)**

The agency's vehicle-related work has traditionally been divided between injury reduction countermeasures (crashworthiness) and crash prevention (crash avoidance). Traditional work in the field of crash avoidance has focused on how essential equipment such as brakes, lights, and tires can be improved to enhance the crash avoidance capability of the driver. Starting about six years ago, the agency began working on how advanced electronics and other technologies could help assist drivers avoid crash. This work is part of the Department of Transportation's (DOT) Intelligent Transportation Systems program. Results of this work have been reported at the last two ESV conferences.

Since the 15<sup>th</sup> ESV Conference, we have made significant progress in improving our understanding of how crash avoidance systems need to work if they are to be effective in helping reduce the number of crashes that occur. Some of that work is being reported in the technical sessions of this conference. This work is the cornerstone for a broader program which DOT started about one year ago. The program is called the Intelligent Vehicle Initiative (IVI).

The IVI program emphasizes development and deployment of advanced-technology vehicle-related injury prevention and safety systems. Although the emphasis of IVI is on safety improvements, there is a strong connection with improving efficiency of travel. For example, crashes often cause nonrecurring congestion. Thus, any collisions that can be avoided help reduce congestion and improve traffic flow. There are also systems which improve a non-safety service but secondarily improve safety; for example, high fidelity map data bases. In addition to the focus on improvements in safety, the IVI will provide a synergistic relationship between vehicle-related aspects of transit operation, passenger vehicle systems, and commercial vehicles. This means that within DOT; NHTSA, Federal Highway Administration (FHWA) and Federal Transit Administration (FTA) will be working more closely together as one DOT than they have in the past. We believe that this closer working relationship will provide opportunities for cross-fertilization and more effective utilization of technologies as they become available.

NHTSA's primary role in IVI is to serve as a facilitator in development and deployment of crash



**Figure 2.** Fatalities for Male and Female Drivers.

avoidance motor vehicle systems. We have several capabilities that we think are critical to the successful development of vehicle-related safety systems. We bring an in-depth understanding of the injury consequences of crashes and of how and why they occur. For example, a recent suggestion is that "DOT's most useful contributions would be in conducting research to identify safety needs and understand driver behavior, sponsoring fleet evaluation programs, and helping to educate consumers on the costs, benefits and correct use of ITS products." A key element of doing this type of research is to have a good understanding of how a system must work if it is to truly provide an effective solution to an identified safety problem. This provides a solid basis for definition of objectives and specification of system performance requirements. For example, a recent study has extended the results of an experiment in a driving simulator to develop a set of criteria for when an imminent crash warning should be activated. This study took into account the dynamics of vehicle motion as well as the results of a human factors test to provide one of the core elements of a collision avoidance system. This type of study represents the essence of human-centered engineering and is an

example of one of the ways that DOT can facilitate development of effective safety-improvement systems. This study is the subject of one of the poster sessions at this conference.

NHTSA's crash avoidance program has made significant progress during this year, including:

1 - A field operational test of an adaptive cruise control system was completed. This test consisted of 10 passenger cars each of which was equipped with a state-of-the-art adaptive cruise control system. Data was collected on this fleet of vehicles for a year. A full evaluation of results is currently underway.

2 - Another project addressed the producibility of key components of collision avoidance systems. The project addresses system components such as sensors, both radar and laser, and head-up displays. Three generations of forward-looking radar sensors were developed during this project and significant progress was made in reducing the manufacturing cost of these sensors and in improving performance. Major improvements were also made in manufacturing techniques and performance, e.g. brightness, of

reconfigurable head-up displays. The project also demonstrated significant improvements in system performance and in understanding the nature of driver interactions with collision avoidance systems. The results of this project will be combined with results from other NHTSA projects to form the basis for an operational test of a rear-end collision avoidance system.

3 - An operational test of an Automatic Collision Notification system is currently in progress. The system integrates state-of-the-art sensors and communication capability and automatically connects the vehicle with the local Emergency Medical Services (EMS) dispatcher and the receiving hospital or trauma center. Base-line time-of-crash data is being collected for 4,000 vehicles equipped with crash event timers. The objective of the field operational test is to design and field test a prototype system for passenger vehicles that automatically and reliably detects the occurrence of a crash and alerts EMS agencies. The ACN program is intended to reduce the time between the crash and the delivery of prehospital and definitive, hospital-based emergency services to the victims. It will do this by automatically assembling and transmitting a cell phone-based data message, that contains the vehicle location and crash severity data, from the vehicle car to local emergency agencies.

4 - NHTSA recently completed an estimate of benefits that would accrue to the driving public if all vehicles were equipped with just three collision avoidance systems: rear-end, road departure, and lane change. The conclusion was that these systems could reduce the number of collisions by 1.1 million per year in the United States. That represents 17 percent of the current number of crashes. This would also represent economic savings of \$26 billion per year. An additional benefit would be the reduction in non-recurring congestion that results from crashes.

DOT recently published a Federal Register notice-request for information (RFI) that would help provide guidance for the intelligent vehicle initiative. The RFI that included a proposed top-level roadmap of how the IVI could move from problem definition to demonstrated performance of preproduction systems and a list of 26 initial services that are candidates for proving motor vehicle safety and travel efficiency. A key element of the roadmap is the development of individual services coupled with operational tests and other evaluation activities to assess the safety and efficiency benefits to highway users. This will be followed by integration of proven services, which

would also be coupled with further evaluation. The RFI also asks for expressions of interest in the program, steps that need to be taken to ensure an effective research and development program, and other areas of needed research.

### **Driver/Vehicle Performance**

The interaction between the driver and vehicle is a key element in highway safety. With the advent of high-technology systems to improve safety, increase productivity and/or provide greater convenience, the driver is now faced with the increasingly difficult task to assimilate this new information and still safely perform the functions of driving. NHTSA's Driver/Vehicle Performance program conducts research into the interaction between the human and the vehicle, supporting both the Intelligent Vehicle Initiative (IVI) and the agency's more traditional crash avoidance safety improvement programs. Key areas of research include understanding driver/ vehicle performance in naturalistic settings, assessing the safety impact of in-vehicle devices like cellular telephones and navigation systems, and assessing the improvement in safety afforded by new intelligent vehicle technologies.

Measuring driver behavior and performance in naturalistic settings has been achieved using the Data Acquisition System for Crash Avoidance Research (DASCAR). This is a suite of instrumentation that was developed by NHTSA for simultaneous measurement and recording of driver and vehicle behavior during long-term exposure to actual on-road driving experiences. A standardized protocol for the collection and archiving of data collected by DASCAR has also been developed. One of the most important advantages of DASCAR is that it is unobtrusive. The driver does not see the sensors and therefore is not likely to be influenced by the fact that his or her actions are being recorded. The system is also easily installed in any vehicle, so that it can be used in privately-owned vehicles under normal driving situations. NHTSA currently has about a dozen DASCAR systems supporting all types of driver behavioral research.

In order to develop collision avoidance countermeasures that will work effectively, it is necessary to first develop a good understanding of how drivers drive without the help of such systems. This year the agency is using DASCAR to record normative "baseline" driver behavior in roadway departure and rear-end collision scenarios. Data are being gathered in actual driving situations to determine how drivers react in "near miss" situations. This information will be used as part of the development of performance

specifications for proposed collision avoidance systems and associated driver/vehicle interfaces.

Another key area of research addresses the safety impact of new in-vehicle technologies. The agency recently published a report regarding the safety implications of using wireless communication devices while driving. Although the study focused on the use of popular cellular telephones, we believe it also provides insight into possible problems that could result from the use of other in-vehicle devices that require the driver to take physical or mental actions that would divert attention away from the driving task. Other studies are investigating the issue of driver workload in general.

Research has also focused on drowsy driving. This work has produced a highly reliable measure of drowsiness, called PERCLOS, defined as the percentage of eyelid closure over time. A prototype system to measure PERCLOS has been developed, and is currently being tested in actual service on overnight runs by a trucking company. Research is being initiated this year to investigate how such a device might be best used to enhance safety. For example, we want to encourage drivers to pull off the road and rest when drowsiness is detected, rather than using the detection device to help them drive longer, which could possibly result in an even greater risk.

Other research addresses driver acceptance and usability of new technology. Any benefits that are predicted for new intelligent vehicle systems are based on the assumption that drivers will make use of the systems, and use them properly. However, if drivers perceive the systems as being unreliable, annoying, or too prone to false alarms, or if the operation of the systems is confusing to drivers, they may ignore or even disable the systems, thus negating any positive benefits. Therefore, the usability of new technology is being addressed as a key factor in assessing the improvement in safety afforded by new collision avoidance systems.

### **Heavy Vehicles**

Although heavy vehicles comprise a relatively small percentage of the vehicles on the road, their high exposure in terms of annual miles driven, along with their size, mass and other physical characteristics, makes them over-represented in terms of involvement in serious crashes. The purpose of NHTSA's Heavy Vehicle Research Program is to foster improvements to heavy vehicle safety.

Much of this research is aimed at improvements to braking. Several years ago the agency conducted a large-scale operational test of antilock braking systems

(ABS), before mandating their use on new heavy vehicles. Current programs are developing improved performance tests for ABS. For the future, electronically-controlled braking systems (EBS), especially if used in conjunction with air disc brakes, offer the possibility of significant improvements in stopping capability and stability for heavy vehicles. The use of EBS would also make possible the deployment of a system developed by NHTSA to selectively brake individual wheels to stabilize vehicles during cornering maneuvers. This system would suppress the phenomenon of "rearward amplification," which often induces rollover in multiple-trailer combinations.

Heavy vehicles are subject to rollovers, which not only are severe crashes to the occupants of the vehicles involved but also create massive problems in terms of traffic tie-ups. A system has been developed to warn truck drivers as their vehicle approaches the rollover threshold for safe operation. Future research will explore the possibility of linking this on-board system to an infrastructure-based system, in order to notify the driver of an upcoming curve that may produce a rollover in time for the driver to take action to slow the vehicle to a safe speed.

Work is also continuing to improve the occupant protection aspects of heavy truck cabs, and to support possible future rulemaking regarding truck tire performance and brake lining performance rating.

### **National Advanced Driving Simulator**

The National Advanced Driving Simulator (NADS) program has advanced from the design phase to the fabrication phase, after a successful Critical Design Review in May 1997. The official ground breaking for the building that will house the NADS facility at the University of Iowa's Oakdale Research Park was held in October 1997, and construction is underway. The simulator, which will be operated by the University of Iowa, is expected to go on-line in early 2000.

NADS will be the world's most technically sophisticated research driving simulator when it becomes operational. Its mission is to dramatically improve highway safety by studying the complex driver performance and behavior issues involved in potential crash situations. It will allow such research to be conducted for the first time in the safety, controlled, and repeatable confines of the research laboratory. Such research will inevitably lead to the development of new vehicle safety systems that will reduce fatalities and injuries on the road. The cutting-edge technology employed by NADS will also provide the capability for

evaluating the advanced vehicle communication, navigation and control technologies which are now being developed as part of the ITS program, and which will begin to appear in automobiles in the near future. Highway engineering and design research related to traffic safety also will be performed.

## **CRASHWORTHINESS RESEARCH**

### **Vehicle Aggressivity and Compatibility**

Light trucks and vans (LTVs) currently account for over one-third of registered U.S. passenger vehicles. Yet, collisions between cars and LTVs account for over one half of all fatalities in light vehicle-to-vehicle crashes. Nearly 60 percent of all fatalities in light vehicle side impacts occur when the striking vehicle is an LTV. In 1996 LTV-car crashes accounted for 5,259 fatalities. In these crashes, 81 percent of the fatally-injured were occupants of the car. These statistics suggest that LTVs and passenger cars are incompatible in traffic crashes, and that LTVs are the more aggressive of the two vehicle classes. In particular, crashes with an LTV cause a disproportionate number of vehicle-to-vehicle fatalities.

NHTSA has initiated a research program to investigate the problem of vehicle aggressivity and compatibility in multi-vehicle crashes. The near term goal is to identify and demonstrate the extent of the problem of incompatible vehicles in vehicle-to-vehicle collisions. The objective is to identify and characterize compatible vehicle designs with the expectation that improved vehicle compatibility will result in large reductions in crash related injuries. Specifically, this program seeks to identify those vehicle structural categories, vehicle models, or vehicle design characteristics which are aggressive based upon crash statistics and crash test data. Light truck and van collisions with cars are one specific, but growing, aspect of this larger problem.

### **Frontal Crash Protection**

Even after full implementation of driver and passenger air bags as required by FMVSS No. 208, it has been estimated that frontal impacts will account for up to 8,000 fatalities and 120,000 AIS  $\geq 2$  (i.e., moderate to critical) injuries annually in light vehicles. A detailed definition of the remaining safety problems in frontal impacts is underway. Research will investigate real world crash environments and project occupant injuries that will occur for an all air bag fleet. This includes summarizing the human loading and

injury tolerances for occupants restrained by air bags in frontal crashes.

This program focuses on the intrusion-type injuries and fatalities and the costly lower extremity injuries observed in crashes involving air bag-equipped vehicles. We believe an offset frontal test best represents the real world crashes that produce the intrusion-related injuries and fatalities and the severe lower extremity injuries. We have been working to develop an offset frontal test, and we have been considering what new injury modes, injury criteria, and test surrogates might be necessary for this type of test.

An analysis of real world crash data using the National Automotive Sampling System (NASS) has been completed and is reported on in a paper "Determination of Frontal Offset Test Conditions Based on Crash Data" for this ESV Conference. Using NASS, frontal impact modes are grouped into general "test" conditions which will best represent the real world impact environment. These general test conditions include full barrier, left and right offset, with collinear and oblique impact directions, and other impact modes. Using these general groupings of impact conditions, the analysis further assesses degree of overlap and impact direction to determine more specifically which crash conditions result in highest injury/fatality to drivers with air bags. Injury/fatality risk is also assessed by driver size and body region/injury source, with a more detailed analysis of leg injuries. Finally, a preliminary benefits analysis is presented for a future, recommended test procedure. Based on this analysis, the offset crash test which represents crash configurations with the highest frequency and risk of serious to fatal injuries is a left offset/oblique, vehicle-to-vehicle impact with substantial overlap. Based on various assumptions, a requirement for a left oblique/offset test procedure could save as many as over 1,000 fatalities, 5,000 AIS  $\geq 3$  injuries and over 20,000 AIS  $\geq 2$  injuries each year. Leg injuries alone could be reduced annually by about 11,000 for AIS  $\geq 2$  and about 2,000 for AIS  $\geq 3$ .

Most recently the offset crash testing has focused on a left oblique type impact for the target vehicle. The nominal test condition is a 30 degree left oblique impact with about 50 to 60 percent overlap on the target vehicle and a closing velocity of about 110 kmph. A 50th-percentile Hybrid III dummy is used as the test surrogate in the driver's seating position. As reported at the last ESV Conference, an initial test in this configuration caused a mid-size vehicle to exceed the FMVSS No. 208 chest and femur criteria. To standardize the test and achieve repeatability, the test is simulated using a moving-deformable-barrier (MDB) to stationary vehicle impact, with a closing speed of

about 110 kmph and an impact angle which best simulates the vehicle-to-vehicle test. Comparison testing has been conducted with car-to-car, MDB-to-car (both moving), MDB-to-car (stationary car) to assess whether the latter test is an adequate substitute for the car-to-car test. Initial assessments indicate that most injury measures and structural responses are fairly similar in the three test configurations. Initially a closing velocity angle of 15 degrees was used and the vehicle was "crabbed" to achieve the 30 degree vehicle-to-vehicle impact configuration. These conditions, besides adding complexity, required substantial refurbishment of the MDB after each test. Currently tests are being conducted to assess the simulation validity for an impact angle between 15 and 30 degrees with no crabbing of the MDB.

### **Side Impact Research**

An analysis of the 1988-1996 NASS/CDS and FARS files indicates that side crashes result in over 11,200 fatalities and 36,000 serious injuries each year to occupants of passenger cars and light trucks and vans (LTVs). This corresponds to about 33 percent of the fatalities and 37 percent of the serious injuries in all towaway crashes. Since the last ESV conference, side crash protection research has mainly focused in three areas—development of a pole side impact test procedure, international harmonization research, and analytical modeling studies. Currently, an overall research plan is being developed to upgrade the dynamic Federal Motor Vehicle Safety Standard No. 214, Side Impact Protection, which established minimum requirements for thoracic and pelvic protection for the near-side occupant in side crashes of light vehicles. Analyses have been initiated to provide a detailed definition of the current side impact safety problem.

In a joint program with the Federal Highway Administration to explore protection of light vehicle occupants involved in side crashes with narrow objects, a series of pole side impact tests with the Honda Accord was performed. The crash testing established the seating procedure and feasibility of an optional pole side impact crash test for the current FMVSS No. 201, Upper Interior Protection, rulemaking addressing dynamic head protection systems. The FMVSS No. 201 optional pole test conditions are within the guidelines of a test procedure simulating a narrow object side crash as established by a general look at recent NASS/CDS and FARS crash data files.

### **Advanced Air Bag Technology Research**

In recent years, a number of crashes have been reported where injuries and fatalities have been the result of aggressive air bag deployment; that is, the severity and crash environment did not warrant the severity of injury/fatality sustained by the occupant. Those most susceptible to injuries/fatalities from aggressive air bag deployments include out-of-position child passengers, out-of-position adult drivers (usually unbelted), and infants in rear-facing child safety seats. As of March 1, 1998, over 100 airbag related fatalities have been identified. A majority of these fatalities have occurred with unrestrained occupants. About 60 percent are fatalities in children and the remaining are adults.

On March 19, 1997, NHTSA published a final rule that temporarily amends the agency's occupant crash protection standard to ensure that vehicle manufacturers can quickly redesign air bags so that they inflate less aggressively. More specifically, the agency adopted an unbelted sled test protocol as a temporary alternative to the standard's full scale unbelted barrier crash test requirement. The agency took this action to provide an immediate, interim solution to the problem of the fatalities and injuries that current air bag systems are causing in relatively low speed crashes to a small, but growing number of children and occasionally to adults. A research program was defined to upgrade the FMVSS No. 208 injury criteria and test devices, and to develop test procedures for evaluation of occupant injury. The objective of this research activity is to eliminate the fatalities and reduce the severity of the injuries resulting from aggressive air bag deployment, while simultaneously optimizing the benefits to normally seated restrained occupants and restoring the full protection for unbelted adults in high severity crashes. The requirements will be established using the state-of-the-art developments of advanced air bag technology.

To define potential areas of improvement with current air bag systems, various analyses of real world crash data are being conducted. The National Automotive Sampling System is being utilized to analyze air bag-related issues such as effectiveness as a function of driver height and gender interaction, specific body region effectiveness estimates for various sub-populations, etc. Other analyses involve investigations of injuries and fatalities with air bags, analysis of fatalities to children under 15 with air bags, and analysis of injuries/fatalities to adult drivers, specifically to identify cases of air bag aggressiveness contributing to the injuries/fatalities. NHTSA's Special Crash Investigation (SCI) program is one of the main utilities for sending quick reaction investigators



to the crash site when NHTSA learns of serious air bag crashes.

With the introduction of new-generation air bag equipped vehicles into the fleet, NHTSA's SCI program also is investigating the field performance of production new-design air bag equipped vehicles through crash investigations, and has implemented several early notification mechanisms to identify these crashes. NHTSA also has conducted laboratory testing to evaluate the aggressiveness of production next-generation air bag systems in new vehicles. High speed crash tests and static out-of-position tests were conducted on a sample of production vehicles, and results were compared with the pre-1998 air bag designed systems.

To assess the potential of advanced air bag technology for improving air bag performance beyond what is achieved with the current new generation of air bags, NHTSA and NASA's Jet Propulsion Laboratory (JPL) conducted an assessment to identify critical air bag parameters, technology advancement needs, and the time frame for advanced technology availability.

To experimentally assess the potential for advanced air bag technology, NHTSA is conducting testing over a wide range of conditions. Initial hardware evaluations have included advanced crash sensors, advanced air bag inflators, and occupant position sensors. NHTSA has recently completed extensive testing on a vehicle platform equipped with a multistage air bag system and advanced crash sensor. Research included out-of-position tests with small female driver and child passenger test dummies, sled testing with small and large adult dummies representing moderate severity crashes of varying crash configuration and restraint application, and high-speed, full-vehicle crash tests to test complete system performance.

Research is being conducted to develop test procedures for evaluating advanced air bag system performance. To minimize air bag risks to occupants in close proximity to the air bag at the time of deployment, static driver and child out-of-position test procedures have been developed; research is being conducted to develop test procedures to evaluate air bag suppression systems (quasi-static and dynamic); and research is being conducted to develop a full scale dynamic crash test involving pre-impact braking. NHTSA also is working on a joint research program with Transport Canada to develop a low speed deformable offset crash test procedure utilizing small female dummies, as well as evaluating the occupant protection afforded to small females in high speed crash conditions.

In conjunction with the development of new test procedures, NHTSA is working toward the certification of alternative test dummy sizes, such as the 3-year-old and 6-year-old Hybrid III children, the 12 month CRABI dummy, and the 5th percentile female and 95th percentile male Hybrid III adults. Calibration procedures, out-of-position testing, and sled testing are being performed with these dummies. NHTSA is conducting numerous experimental and analytical research programs in biomechanics to improve the human injury tolerance relationships used to interpret dummy responses across the full spectrum of test dummy sizes. Two major areas of research are in the development of improved thoracic and neck injury criterion as these will be used to account for a large number of air bag induced injuries and fatalities in the field due to the impulsive loading of the air bag system. Additionally, a research program has been initiated to investigate improvements that can be made to test dummies to properly mimic the characteristics of human occupants for use in testing advanced occupant sensors that utilize technologies such as infrared and capacitive sensing.

### **Biomechanics Research**

Our National Transportation Biomechanics Research Center (NTBRC) conducts a wide variety of research projects to develop a better understanding of occupant injury mechanisms and tolerances in the automotive crash environment. Injuries attributed to contact with the vehicle's occupant compartment and various restraint systems have been investigated through both experimental testing and computational analyses. Results from this research provide the basis for the development of safety standards, injury criteria, anthropomorphic dummies, and injury mitigating countermeasures. Biomechanics research is organized into four distinct areas of concentration:

- Crash Injury Research and Engineering Network (CIREN),
- analytical modeling and simulation,
- experimental impact injury research, and
- anthropomorphic dummy development.

The Crash Injury Research and Engineering Network, CIREN, has been created to enable physicians, emergency medical services (EMS) professionals, and engineers to better understand mechanisms of crash injury. The network is comprised

of seven trauma centers from around the country, each with particular areas of medical expertise and research interests. These centers include The University of Michigan Medical Center in Ann Arbor, Michigan; the National Study Center for Trauma and Emergency Services in Baltimore, Maryland; the William Lehman Injury Research Center, Ryder Trauma Center in Miami, Florida; the University of Medicine and Dentistry of New Jersey, in Newark, New Jersey; the Harborview Injury Prevention and Research Center in Seattle, Washington; the San Diego County Trauma System in San Diego, California; and the Children's National Medical Center in Washington, D.C.

The implementation of the CIREN network has enabled medical researchers at the seven centers to begin to work in collaboration with researchers in government, industry and academia to provide a multidisciplinary approach to crash injury control. The common computer network linking the seven centers and NHTSA, which will be completed by this spring, is expected to produce (1) common data formats and retrieval methods for collecting, storing, and retrieving crash injury information; (2) comprehensive and detailed vehicle and patient data from about 350 crashes per year; (3) a database for controlled access by medical and automotive engineering researchers worldwide to study crashes, injuries, and medical outcomes; (4) multidisciplinary case reviews to improve the understanding of crash biomechanics by physicians and the medical consequences of crashes by engineers; and (5) broad dissemination of research results across the specialties and training of new researchers.

The CIREN network will provide the medical and engineering communities with an early-warning system to detect emerging injury patterns associated with design changes in vehicles and highways. Clinicians will have access to crash information, and the automobile industry will have information with which to design safer vehicles. Finally, governments worldwide can use these results to increase the safety of their citizens.

Analytical Modeling and Simulation has focused primarily on the development and validation of finite element models of the human anatomy. Detailed models have been developed of the head, neck, thorax, lower extremities, and foot/ankle complex. These models include all of the biomechanically significant anatomic structures, including bone, cartilage, ligament, and muscle. In addition to the finite element models being developed, simulations have also been conducted using multi-body dynamics. These models typically represent the full human body as a number of rigid bodies, joined together by a combination of joints.

Computational simulations have provided insight into the complex mechanism of automotive crash related trauma. A number of specific injury mechanisms have been investigated through computational simulations, including:

- serious brain injury resulting from upper interior impact,
- diffuse axonal injury resulting from rotational acceleration of the head,
- serious cervical spine injury caused by compressive loading due to head impact,
- minor neck injury caused by rear impact whiplash conditions,
- thoracic trauma caused by seat belt loading and side impact,
- thoracic trauma resulting from out-of-position air bag deployment, and
- ankle injury resulting from floor pan intrusion.

Experimental Impact Injury Research provides critical data on injury mechanisms and tolerances for a variety of loading configurations. Since it is impossible to subject human volunteers to injurious crash situations, testing on cadaveric specimens provide the closest similarity. Anthropomorphic dummy tests are also conducted to relate human injury phenomena to a more repeatable and robust test system. There are currently over 1,400 human surrogate tests and 2,250 dummy tests contained within the Biomechanics Database. This test data, along with analytical simulations, has highlighted a number of injury mechanisms for various regions of the body.

In 1984, the results from 49 side impact cadaver tests were published. These data indicated that injuries to the rib cage and the underlying organs are strongly related to the peak lateral acceleration experienced by the struck side ribs and the lower thoracic spine. Subject age and mass also had an influence on the susceptibility to injury. A relationship called the Thoracic Trauma Index (TTI) was developed based on these experimental results.

One major achievement which has dramatically improved our ability to measure the response of the thorax to impact conditions was the invention of the External Peripheral Instrument for Deformation Measurement in 1989. This device, more commonly

referred to as the chestband, consists of a thin steel band instrumented with strain gage bridges located every inch along its length. These devices can be wrapped around a test subject's torso like a belt to record changes in curvature for each gage location around the circumference. Output from the gages are input into an analysis program called EBAND-PC, which calculates the cross-sectional shape of the torso dynamically during an impact event.

In 1990, data from 126 cadaver tests and 222 Hybrid III dummy tests were used to establish a femur load tolerance for a variety of different test conditions. From these tests, it was shown that femur force alone could distinguish between injurious and non-injurious loading scenarios, although a combination of femur force and the rise time of the force was a better predictor of femoral injury. A femur force tolerance value of 12 kN was associated with a 21% risk of femur fracture.

In 1991, 480 in-depth real world crash reports were examined. It was found that lower extremity injuries were 26 percent of the total AIS 3 or greater injuries. For most of these foot/ankle injuries the amount of floor pan intrusion was low. This suggested a prominent foot/ankle injury mechanism associated with a slapping force to the foot.

In 1995, a paper was presented at the 39th Stapp Conference describing the response of the torso to a variety of seat belt and air bag combinations. Results from 13 cadaver and 4 dummy tests were shown air bags alone and in combination with standard seat belts (6% elongation), compliant seat belts (16% elongation), and 4kN and 5kN force-limiting seat belts. The results showed that for the standard and compliant seat belt systems in combination with an air bag, the thoracic injuries were located along the shoulder belt. A minimal benefit was gained from the presence of an air bag. Test results using force-limiting seat belts showed the potential for achieving the benefits of an air bag, while still maintaining the multi-directional benefits of being restrained by a seat belt.

In 1996, the results from 52 foot/ankle tests were reported. These tests looked at a number of biomechanical parameters to ascertain their relationship to lower extremity injuries. Statistical analyses indicated that the two most significant variables were dynamic axial force and subject age. Research into the mechanisms and tolerances of the foot/ankle complex are continuing, looking at a number of other parameters such as loading rate and initial position of the foot. To date, over 100 tests have been conducted to investigate lower extremity injuries.

In 1997, data from 22 cadaver head/neck specimens were presented at the 41st Stapp

Conference. These tests highlighted the complex coupling that exists between the head and neck, as well as the buckling behavior of the cervical spine. Results showed a significant difference between the load tolerance of males and females. According to this study, the female failure load was roughly 1.0 kN, while for the male it was more than double this value.

Understanding the complex response and interactions of the human body during an automotive impact event is a difficult task. As discussed above, real world crash investigations, analytical modeling, and experimental impact testing have attempted to develop this knowledge. However, before this can be applied to a regulation, a robust and repeatable test device must be available. NHTSA Biomechanics has conducted several major initiatives in the area of anthropomorphic dummy development.

In 1992, a collaborative research project with the University of Michigan Transportation Research Institute was completed. This project was to develop and test a new thorax assembly that would improve dummy performance with regard to restraint system interaction and injury sensing capability for the chest and abdomen. New features of this dummy thorax, known as the Trauma Assessment Device (TAD), included a rib cage with more human-like geometry based on the anthropometry study of 1983. Also included were an articulated thoracic spine, shoulders with load bearing clavicles connected to a sternum with improved range of motion, a frangible abdomen, and a chest deflection measurement system capable of monitoring three-dimensional displacements of the rib cage at multiple locations.

Following on to the TAD thorax development, a new complete frontal dummy, known as the Test-device for Human Occupant Restraint (THOR), was developed and presented at the 1996 ESV Conference. This new complete dummy incorporates all of the latest knowledge acquired from NHTSA's biomechanical testing and simulation. Almost every part of the body was completely re-designed, and exhibits a more biofidelic response than its predecessor. The THOR dummy is currently undergoing a thorough evaluation from numerous international collaborators. Enhanced instrumentation in all anatomic regions of the dummy allows for the collection of vast amounts of data critical to the prediction of injuries. Following evaluation of the mid-sized male THOR dummy, a family of adult dummies will be developed.

Another area in which the National Transportation Biomechanics Research Center has been active is hosting scientific conferences and workshops. Every year, scheduled around the Stapp Car Crash Conference, the International Workshop on Human

Subjects for Biomechanical Research is held. This Workshop celebrated its 25th anniversary back in November. It is a forum in which biomechanics researchers from around the world can present current work in progress. Receiving feedback from colleagues during the early stages of a research program can help correct problems or limitations in experimental protocols. This also helps to maximize the benefit derived from human subjects testing and to avoid wasting specimens. Papers presented at the Human Subjects Workshop are commonly presented at other scientific conferences, such as the Stapp Conference, once the testing program is completed.

Two additional scientific conferences have also been hosted by NHTSA Biomechanics. In 1994, co-hosted by George Washington University, the International Symposium on Head Injury Research was held in Washington, DC. This conference was designed to provide a forum for the comprehensive discussion of issues related to traumatic brain injury (TBI) and skull fracture. Topics covered included epidemiology of TBI, injury mechanisms, computational and experimental biomechanics, and aspects of treatment and outcome following closed head injury.

In 1995, NHTSA co-hosted the International Conference on Pelvic and Lower Extremity Injuries along with the Maryland Shock Trauma Center and the University of Virginia. This conference was prompted by earlier highway traffic injury studies which provided evidence that pelvic and lower extremity injuries, while not necessarily life-threatening, contributed significantly to the cost and morbidity associated with traumatic injuries. The success of air bags in reducing fatalities and injuries to the head and chest, meant that occupants were surviving more severe crashes, often with severe injuries to the lower extremities. The purpose of this conference was to bring together professionals involved in research, policy, injury prevention and treatment of lower extremity injuries to exchange information and ideas. The conference provided an opportunity for those involved in this work internationally to take stock of ongoing activities and to identify gaps where new research or programs were needed.

### **In-House Testing**

NHTSA's in-house testing laboratory, the Vehicle Research and Test Center (VRTC), located in East Liberty, Ohio, has continued to be an integral part of the agency team since the last ESV conference. VRTC conducts programs in crashworthiness, biomechanics, crash avoidance and defect investigations.

In the biomechanics area, VRTC has been involved in bringing the wide array of Hybrid III dummy sizes into NHTSA safety standards. In addition to the 50<sup>th</sup> male, the 5<sup>th</sup> female, and 3 and 6 year old dummies are being finalized for standards as well as the 12 month old CRABI. A report of child and adult injury criteria was prepared and sent outside the agency for comment. In addition, a survey of vehicles and child restraints was completed, and a CD ROM was prepared for public use assisting parents in identifying which seats are compatible with their vehicle and how to properly install the child restraints.

In the area of vehicle crashworthiness, VRTC conducted testing with baseline and next-generation air bags, which provided the basis for the regulation changes in FMVSS 208. Sled test procedures were developed to replace full scale crash testing as an interim procedure which allows new-generation air bags. Advanced air bag restraint concepts are currently being evaluated. Also, advanced side glazing systems have been developed which minimize ejection and laceration potential in side and rollover crashes. A series of tests to evaluate the aggressiveness of light trucks has been performed, and the results are currently being evaluated.

In the crash avoidance area, VRTC has developed a comprehensive research plan to evaluate the performance of ABS brakes and determine why highway performance has been successful. The research is underway, with approximately half of the 3 years of effort completed. An evaluation of potential test procedures to measure rollover propensity has been performed, and preparations have begun to conduct rollover testing of a subset of the vehicle fleet. Also, an unobtrusive data gathering package has been developed which could be used in volunteer and government vehicles to assess driver performance and behavior. This package, called DASCAR, will be useful in many current and future driver behavior studies. (See ITS section for additional information.)

Over 40 investigations of alleged vehicle defects have been performed at VRTC. The engineering analysis of the presence and consequences of the defects was reported to the Office of Safety Assurance for appropriate action.

### **INTERNATIONAL HARMONIZATION**

Recognition of the need for globally harmonized motor vehicle safety regulations has been reflected in many symposia held around the world over the years. The United States continues to be involved in regional and worldwide regulatory harmonization efforts such as those of the United Nations' Economic Commission

for Europe Working Party on the Construction of Vehicles (WP.29); the Asia Pacific Economic Cooperation's Transportation Working Group (APEC-TPT); and the Automotive Standards Council of the North America Free Trade Agreement (ASC-NAFTA). This is in addition to its involvement in the International Harmonized Research Activities (IHRA). Since the last ESV Conference, significant progress has been made within these fora with respect to the harmonization of motor vehicle safety and environmental regulations.

#### **International Harmonized Research Activities (IHRA)**

Since the last ESV Conference, NHTSA has been working with its international partners to conduct research, establish priorities, and to carry out the agreements reached during the 15th ESV Conference in Melbourne -- International Harmonized Research Activities (IHRA).

The IHRA Steering Committee has met every six months to review recommendations and research plans being developed by the five working groups. In May of 1997, NHTSA, in conjunction with the IHRA Committee, hosted a Public Workshop to share with its partners the goals and objectives of IHRA. The first status reports on progress to date will be presented during this ESV Conference by the five lead country representatives. IHRA research programs include: advanced offset frontal crash protection, intelligent transportation systems, vehicle compatibility, biomechanics, and pedestrian safety.

#### **UN/ECE/WP.29**

Under WP.29, the harmonization efforts of passenger car brakes have led to a greater compatibility among the European, Japanese and US brake regulations. The United States will be using this harmonized regulation as pilot for the regulatory actions required with regard to certifications for those regulations that are harmonized or assessed as functionally equivalent. There has also been progress with respect to the installation of lighting and light-signaling devices on passenger cars conforming to regulatory requirements of the ECE, the US and Japan. Further, work is expected to continue with respect to the consideration of a harmonized passing beam pattern and glare of headlamps. Most importantly, however, significant progress has been made with respect to the establishment of a process for harmonizing and developing global technical regulations.

#### **Agreement on Global Technical Regulations**

During the November 1997 Session of WP.29, confirming the determination to conclude the agreement for establishing global technical regulations to the satisfaction of all parties in the most effective way, the Working Party requested that the representatives of the United States, the EU and Japan prepare by a joint effort and through informal meetings, a new revision of the proposed agreement. The Working Party also requested the Secretariat to circulate it for consideration by other members during the March 1998 session.

During the March 1998 Session of WP.29, the three parties announced that they reached accord on a text to present to the participants of WP.29. The text remains conditioned upon approval of respective authorities. The draft reflects a number of very difficult compromises on all sides, as it involved the union of three very different regulatory systems into one document. It also builds on the many suggestions and formal comments made by other participating countries. Written comments on the current draft were accepted through April 30, 1998, and will be made available for final discussion and negotiation by all interested parties during the June 1998 meeting of WP.29. It is anticipated that a final text will be officially open for signature at that time.

Thus, in the near future, a transparent process for developing global regulations concerning motor vehicle safety will be available and open to participation of all interested countries. The contributions of both developed and developing countries to the process will result in regulations that are adaptable to each country's needs. This process will provide an unprecedented opportunity for cooperative work regarding the development of regulations to serve and protect the respective citizens and environment of participating countries while providing a predictable regulatory framework for a global industry.

#### **Asia Pacific Economic Cooperation**

NHTSA continues to be involved with APEC harmonization projects, as a regular participant in meetings and a contributing member to the development and administration of harmonization activities. Of significance is the Road Transport Harmonization Project (RTHP), which began in 1994, and whose objective is to promote standards harmonization within APEC countries through the collection and analysis of vehicle regulations applied by each of the APEC economies to identify commonalities and divergences. The project

commissioned a consultant to conduct the analysis of commonalities and divergences among identified 71 regulations and to conduct comparisons of functional equivalence models and certification requirements used within the various economies.

The results of this project are of great value to member economies as they establish priorities for harmonization, functional equivalence assessments and marketing decisions. APEC is also keeping abreast of proposals presented by WP29 with respect the Agreement on Global Technical Regulations and other activities under the 1958 Agreement. A seminar was held in April 1998 in Mexico City in order to coordinate efforts.

### **North America Free Trade Agreement**

NHTSA's involvement in NAFTA harmonization efforts is through the Automotive Standards Council. The Council has been working for 2-3 years in order to (1) identify incompatibilities in standards among NAFTA countries; and (2) set up a process that addresses these incompatibilities. Working groups comprised of government and industry personnel have been organized to facilitate the process. These groups have begun working together to make recommendations to resolve current incompatibilities and to identify future divergences.

### **Functional Equivalence Assessment**

On May 13, 1998, NHTSA published a final rule reaffirming the agency's policy of focusing its international harmonization activities on identifying and adopting those foreign regulations that clearly reflect best practices which can provide enhanced safety. The rule amended Part 553, Rulemaking Procedures, of the CFR, by adding a new Appendix setting forth the process in the form of a flowchart which the agency believes meets the concerns expressed in the written public comments and at the public workshop held in January 1997. The agency intends to follow this process in considering whether to commence rulemaking proceedings based on petitions for functional equivalence determination. The final rule also emphasizes the agency's policy to deny any such rulemaking petition if the petition does not contain an analysis of the relative benefits of the two regulations as outlined in the process.

### **Other Harmonization Activities in the US**

The House and Senate Appropriations Committees directed NHTSA to begin work on establishing a

frontal offset standard and developing a plan for achieving harmonization of the side impact standard. During the fiscal year 1998 hearings, NHTSA submitted reports to the Committees outlining the agency's standards development and harmonization efforts with current European and Australian offset crash and side impact regulations. NHTSA is currently working on implementing the plan. The functional equivalence process is a major step of the plan, which includes comparative compliance testing and data analyses.

In summary, the harmonization of regulations has become a matter of increasing importance in the last decade. Efforts to coordinate regulatory practices on a global scale have resulted in establishment of fora and agreements to promote and guide the process of harmonization. NHTSA has been responsive by actively participating in many of these fora while ensuring that any harmonization activity improves the levels of safety and environmental protection.

### **SAFETY PERFORMANCE STANDARDS**

Since the last ESV Conference in Australia, NHTSA has published many new rulemakings. These have included several related to occupant crash protection. The following is a computation of the more significant, ordered in three areas: Crashworthiness, Crash Avoidance, and Consumer Programs.

#### **Crash Avoidance**

- On July 11, 1996 a Final Rule was published in response to petitions for reconsideration, to amend the reservoir requirements in FMVSS 121, "Air Brake Systems," for trucks, buses, and trailers equipped with air brakes to clarify the reservoir requirements.
- On July 12, 1996 a Final Rule was published rescinding FMVSS 126, "Truck-camper Loading," and combining its provisions with Part 575.103, Truck-camper Loading. This action makes their respective requirements easier to understand and apply.
- On August 8, 1996 a Final Rule was published amending FMVSS 108, "Lamps, Reflective Devices, and Associated Equipment," to require that the rear of truck tractors be equipped with retroreflective material similar to that required on the rear of the trailers they tow, to increase nighttime conspicuity and reduce rear end crashes.

- On August 29, 1996 a Final Rule was published to amend FMVSS 108, "Lamps, Reflective Devices, and Associated Equipment," to improve the photometric requirements for motorcycle headlamps.
- On September 23, 1996 a Final Rule was published specifying the location, labeling, color, activation protocol, and photometric intensity of antilock brake systems (ABS) malfunction indicator lamps on the exterior of trailers and trailer converter dollies, under FMVSS 121, "Air Brake Systems."
- On September 24, 1996 a Final Rule was published to transfer most of the requirements of FMVSS 112, "Headlamp Concealment Devices," to FMVSS 108, "Lamps, Reflective Devices, and Associated Equipment," and rescinding the remaining requirements.
- On November 15, 1996 a notice of proposed rulemaking (NPRM) was published to amend FMVSS 118, "Power Operated Window, Partition, and Roof Panel Systems," to improve the safety of children. The amendment would require each power operated window, interior partition and roof panel in a motor vehicle to be equipped with a switch designed so that contact by a form that represents a child's knee would not cause the window, partition, or panel to close.
- On November 29, 1996 a Final Rule was published in response to a petition for reconsideration from the Flexible Corporation to amend FMVSS 121, "Air Brake Systems," with respect to the air pressure at which a bus's air compressor must automatically activate.
- On January 8, 1997 a notice of proposed rulemaking (NPRM) a proposed a new standard FMVSS 100, "Low Speed Vehicles," which would establish classification and safety regulations for small, lightweight, 4-wheeled vehicles that are used on the public roads.
- On March 10, 1997 as a result of a negotiated rulemaking, a Final Rule was published to amend FMVSS 108, "Lamps, Reflective Devices, and Associated Equipment," to improve the accuracy of motor vehicle headlamp aim when headlamps are aimed visually and/or optically.
- On August 6, 1997, in response to a petition for rulemaking from Transpec Corporation, a notice of proposed rulemaking (NPRM) was published to amend FMVSS 131, "School Bus Pedestrian Safety Devices," to permit the use of additional light sources on the surface of retroreflective stop-signal arms.
- On September 5, 1997 a Final Rule was published to amend FMVSS 105, "Hydraulic and Electric Braking Systems," and FMVSS 135, "Passenger Car Brake Systems," to assure the safe performance of brake systems in electric vehicles. The rule addresses the unique characteristics of brake systems on these vehicles, such as regenerative braking.
- On September 30, 1997 a Final Rule was published to extend the stopping distance requirements in FMVSS 135, "Passenger Car Brake Systems," to trucks, buses, and multipurpose passenger vehicles with a gross vehicle weight rating (GVWR) of 3,500 kilograms or less.
- On February 19, 1998 a Final Rule was published to amend FMVSS 108, "Lamps, Reflective Devices, and Associated Equipment," to permit white reflex reflectors designed to be mounted horizontally in trailer and truck tractor conspicuity treatments to be mounted vertically in upper rear corner locations if they comply with appropriate photometric requirements.
- On March 16, 1998 a Final Rule was published to amend FMVSS 105, "Hydraulic and Electric Braking Systems," permitting hydraulically-braked vehicles with a gross vehicle weight rating (GVWR) greater than 10,000 pounds but less than 19,501 pounds to be equipped with a single wheel speed sensor in the drive line to control wheel slip at the drive axle and permits rear tag axles to lock up. In addition, this allows motor homes with a GVWR of 22,500 pounds or less to use a single rear drive axle wheel speed sensor if they are manufactured before March 1, 2001, after which new motor homes must meet the same ABS requirements as other hydraulically-braked trucks and buses.

#### **Crashworthiness**

- On June 18, 1996, in response to petitions for reconsideration, a Final Rule was published on FMVSS 213, "Child Restraint Systems," to correct or clarify provisions of the July 1995 Final Rule to permit manufacturers to produce belt-positioning

seats with a mass on up to 4.4 kg and to permit them to use the word "mass" in labeling child seats.

- On June 19, 1996, an announcement of a public meeting was published to seek information from school bus manufacturers, school transportation providers, and other members of the public on issues related to the transportation of school children.
- On July 29, 1996, in response to a petition for rulemaking, a notice of proposed rulemaking (NPRM) was published on FMVSS 208, "Occupant Crash Protection," proposing a limited extension of the compliance date of a recent rule improving safety belt fit by requiring that Type 2 safety belts installed for adjustable seats in vehicles with a gross vehicle weight rating (GVWR) of 10,000 lbs or less either be integrated with the vehicle seat or be equipped with a means of adjustability to improve the fit and increase the comfort of the belt for a variety of different sized occupants.
- On July 31, 1996, in response to petitions for reconsideration, a Final Rule was published on FMVSS 206, "Door Locks and Door Retention Components," granting the request for a phase-in of the compliance date of the new requirements and established the usual reporting and record keeping requirements necessary for enforcement of a phase-in and clarified the definition of "trunk lid" with respect to vehicles in which the seatbacks of rear seats fold down to provide additional cargo space; other requests denied.
- On August 6, 1996, a notice of proposed rulemaking (NPRM) was published on FMVSS 208, "Occupant Crash Protection," to reduce the adverse effects of air bags, especially those on children.
- On August 12, 1996, in response to a petition for rulemaking, a Final Rule was published on FMVSS 205, "Glazing Materials," to permit the installation of a new item of motor vehicle glazing, Item 4A - Rigid Plastic for Use in Side Windows, in motor vehicles.
- On August 30, 1996, in response to a petition for rulemaking, a notice of proposed rulemaking (NPRM) was published on FMVSS 208, "Occupant Crash Protection," proposing a

provision which specifies that during crash tests, all portions of the test dummy must remain in the vehicle throughout the test.

- On September 6, 1996, in response to petitions for reconsideration, a Final Rule was published on FMVSS 304, "CNG Fuel Container Integrity," modifying the labeling requirements with respect to the inspection interval and deleted reference to certain pamphlets.
- On September 10, 1996, in response to petitions for rulemaking, a notice announcing a public meeting on FMVSS 213, "Child Restraint Systems," on a workshop to explore issues relating to improving child safety by establishing requirements for universal child restraint anchorage systems.
- On September 24, 1996, a notice of proposed rulemaking was published on part 572, "Anthropomorphic Test Dummy," proposing specifications for the side impact test dummy and the procedure in the agency's side impact protection standard for positioning the dummy in a vehicle for compliance testing purposes: 1) add plastic inserts-spacers to the dummy's lumbar spine and 2) specifies that the ribcage damper piston of the dummy is set during the dummy positioning procedure to the fully extended position prior to the side impact dynamic test.
- On November 27, 1996, a Final Rule was published on FMVSS 208, "Occupant Crash Protection," requiring new attention-getting labels to reduce the adverse effects of air bags unless the vehicles have a "smart" passenger-side air bag.
- On December 12, 1996, a request for comments was published on FMVSS 202, "Head Restraints," requesting comments on a Technical Report titled, "Head Restraints-Identification of Issues Relevant to Regulation, Design, and Effectiveness.
- On December 26, 1996, in response to several petitions for rulemaking, a Final Rule was published on part 572, Anthropomorphic Test Dummy," amending the specifications for the Hybrid III compliance test dummy.
- On January 2, 1997, a technical amendment was published on FMVSS 208, "Occupant Crash Protection," correcting errors in warning label



requirements in the final rule published on November 27, 1996.

- On January 6, 1997, a Final Rule was published on FMVSS 208, "Occupant Crash Protection," extending until September 1, 2000, the time period during which vehicle manufacturers are permitted to offer manual cutoff switches for the passenger-side air bag for vehicles without rear seats or with rear seats that are too small to accommodate rear facing infant seats.
- On January 6, 1997, a notice of proposed rulemaking (NPRM) was published on FMVSS 208, "Occupant Crash Protection," proposing occupant protection standard to ensure that vehicle manufacturers can redesign all air bags so that they inflate less aggressively.
- On January 6, 1997, a notice of proposed rulemaking (NPRM) was published on FMVSS 208, "Occupant Crash Protection," proposing as part of its efforts to address the problem of the adverse effects of current air bag designs on children and certain adults, to make it possible for vehicle owners to have their air bags deactivated by vehicle dealers and repair businesses.
- On January 10, 1997, in response to a petition for rulemaking, a Final Rule was published on FMVSS 208, "Occupant Crash Protection," granting a four-month extension of the date by which vehicles with a gross vehicle weight rating (GVWR) of more than 8,500 pounds and less than 10,000 pounds must comply with the requirements for safety belt fit.
- On January 21, 1997, a notice announcing a public workshop on FMVSS 208, "Occupant Crash Protection," to explore technical issues relating to the occupant protection standard and smart air bags.
- On February 20, 1997, in response to several petitions for rulemaking, a notice of proposed rulemaking (NPRM) was published on FMVSS 213, "Child Restraint System," proposing to require motor vehicles and add-on child restraints be equipped with a means independent of vehicle safety belts for securing the child restraints to vehicle seats.
- On February 27, 1997, a request for comments was published on FMVSS 208, "Occupant Crash Protection," seeking comments on whether to amend the provisions in the standard concerning the use of unbelted as well as belted dummies in testing air bag-equipped vehicles.
- On March 19, 1997, a Final Rule was published on FMVSS 208, "Occupant Crash Protection," to temporarily amend the standard to ensure that vehicle manufacturers can quickly redesign all air bags so that they inflate less aggressively.
- On April 8, 1997, in response to several petitions for reconsideration, a Final Rule was published on FMVSS 201, "Occupant Protection in Interior Impact," to include another phase-in option, allowing manufacturers to carry forward credits for vehicles certified to the new requirements prior to the beginning of the phase-in period, exclude buses with a gross vehicle weight rating (GVWR) of more than 8,500 pounds, specifying that all attachments to the upper interior components are to remain in place during compliance testing, and making other changes to the test procedure clarifying some areas of confusion.
- On April 17, 1997, in response to a request from an automobile manufacturer, an Interim Final Rule; request for comment was published on FMVSS 213, "Child Restraint Systems" modified the air bag warning label which rear-facing child seats are required to bear beginning May 27, 1997, and requested comments on this amendment.
- On April 21, 1997, a notice of proposed rulemaking (NPRM) was published proposing Phase II of metric measurements conversion from English.
- On May 14, 1997, in response to a request from AAMA, an Interim Final Rule; request for comments was published on FMVSS 208, "Occupant Crash Protection," a temporary amendment to ensure that vehicle manufacturers can quickly redesign all air bags so that they inflate less aggressively and requested comments on this amendment.
- On May 20, 1997, an Interim Final Rule; request for comment was published on part 572, "Anthropomorphic Test Dummy," adopting modifications to the Hybrid III test dummy, which is specified by the agency for use in compliance testing under FMVSS 208, "Occupant Crash Protection," to require a six axis neck transducer to

ensure compliance with the recent amendment to allow air bag redesign and requests comments on this final rule.

- On May 20, 1997, a request for comment was published seeking comments on the agency's response to the recommendations of the National Academy of Sciences study titled "Shopping for Safety—Providing Consumer Automotive Safety Information."
- On May 20, 1997, in response to a petition for rulemaking, the agency will evaluate concerns for emergency handling test (for sport-utility vehicles) as the agency continues to be interested in rollover safety.
- On May 30, 1997, in response to petitions for rulemaking, a notice of proposed rulemaking (NPRM) was published on FMVSS 304, "CNG Fuel Container Integrity," proposing to delete the material and manufacturing process requirements because of the most recent proposed voluntary industry standard.
- On June 5, 1997, in response to a request from an automotive manufacturer, an Interim Final Rule; request for comment was published on FMVSS 213, "Child Restraint System," to modify the air bag warning label which rear-facing child seats are required to bear and requested comments on this amendment.
- On July 7, 1997, in response to a petition for rulemaking, a notice of proposed rulemaking (NPRM) was published on FMVSS 209, "Seat Belt Assemblies," proposing to delete the requirement in S4.1(b) that the lap belt portion of a safety belt system be designed to remain on the pelvis under all conditions.
- On August 7, 1997, a notice of proposed rulemaking (NPRM) was published on part 572, "Anthropomorphic Test Dummy," proposing minor modifications to the test dummy's clothing and shoes and the hole diameter in the femur flange in the pelvis bone flesh to facilitate compliance testing.
- On August 20, 1997, in response to a petition for rulemaking, a Final Rule; Technical Amendment was published on part 572, "Anthropomorphic Test Dummy," correcting the specification

characteristics of the test dummy representing a six-year-old child.

- On August 26, 1997, a notice of proposed rulemaking (NPRM) was published on FMVSS 201, "Occupant Protection in Interior Impact," proposing to permit, but not require, the introduction of dynamic head protection systems currently being developed by vehicle manufacturers to provide added lateral crash protection.
- On August 26, 1997, as a request from AAMA, an Interim Final Rule was published on FMVSS 208, "Occupant Crash Protection," to further amend the occupant crash protection standard, so that a special, less stringent test requirement in the related standard, interior protection, that applies to vehicle certified to the unbleaded barrier test will also apply to vehicles certified to the alternative sled test.
- On November 21, 1997, a Final Rule was published on FMVSS 208, "Occupant Crash Protection," allowing motor vehicle dealers and repair businesses to install retrofit manual on-off switches for air bags in vehicles owned by or used by persons whose requests for switches have been approved by the agency.
- On December 1, 1997, a Termination was published on FMVSS 301, "Fuel System Integrity," terminating rulemaking in which the agency had considered to limit fuel spillage experienced by vehicles equipped with a crossover fuel line.
- On December 8, 1997, a notice of proposed rulemaking (NPRM) was published on part 572, "Anthropomorphic Test Dummy," specifying requirements for a newly developed anthropomorphic test dummy for compliance testing of head impact protection.
- On December 30, 1997, a Final Rule was published on FMVSS 208, "Occupant Crash Protection," correcting language of the regulatory text to clarify the requirement of key specifically matched to the on-off switch and how the readiness indicator should function when one or both air bags have been deactivated by means of the on-off switch.

- On January 26, 1998, in response to a petition for rulemaking, a Final Rule was published on FMVSS 208, "Occupant Crash Protection," amending the requirements for seat belts at forward-facing rear outboard seating positions of police cars and other law enforcement vehicles to facilitate the transporting of prisoners.
- On January 26, 1998, in response to petitions for reconsideration, a Final Rule was published on FMVSS 223, "Rear Impact Guards" and FMVSS 224, "Rear Impact Protection," to clarify the 100mm (4 inch) height requirement for the horizontal member of an underride guard, explicitly exclude from having to meet the energy absorption requirements all cargo tank motor vehicles manufactured with rear end protection complying with the high strength requirements of 49 CFR part 178 (to protect hazardous material) that occupies the area specified for the underride guard, and increases the acceptable range of force application rates during testing. This excludes pulpwood trailers from the application of the vehicle standard and denies a petition to extend the effective date of the final rule published January 24, 1996.
- On February 4, 1998, in response to petitions for reconsideration, a Final Rule was published on part 572, "Anthropomorphic Test Dummy," making minor modifications in the dummy's femurs and ankles to improve biofidelity.
- On April 2, 1998, a Final Rule was published on FMVSS 208, "Occupant Crash Protection" and part 572, "Anthropomorphic Test Dummy," making two amendments to the specifications for the side impact test dummy and the procedures in the side impact protection standard for positioning the dummy in a vehicle for compliance testing purposes.
- On April 2, 1998, in response to a petition for rulemaking, a withdrawal was published on FMVSS 208, "Occupant Crash Protection," withdrawing the proposed rulemaking which considered allowing partial ejection of the Hybrid III dummy during crash tests.
- the agency made a limited, temporary amendment to its content calculation procedures to provide vehicle manufacturers added flexibility in making content determinations where outside suppliers have not responded to requests for content information; and requested comments on whether to provide this or similar added flexibility for a longer period of time.
- On September 9, 1996, a Final Rule was published on part 575.104, "Uniform Tire Quality Grading (UTQGS)," revising the treadwear testing procedures to maintain the base course wear rate of course monitoring tires at its current value of 1.34.
- On January 3, 1997, a notice of proposed rulemaking (NPRM) was published on part 538, "Manufacturing Incentives for Alternative Fuel Vehicles," proposing to set the minimum driving range only for dual fueled electric passenger automobiles, otherwise known as hybrid electric vehicles (HEVs) at 17.7 miles when operating on electricity alone.
- On April 3, 1997, a Final Rule was published on part 533, "Light Truck Fuel Economy," establishing the average fuel economy standard for light trucks manufactured in model year (MY) 1999 as 20.7 mpg.
- On June 23, 1997, in response to petitions for reconsideration, a Final Rule was published on part 583, "Automotive Parts Content Labeling," extending for two years a limited, temporary provision in its content calculation procedures to provide vehicle manufacturers added flexibility in making content determinations where outside suppliers have not responded to requests for content information.
- On April 13, 1998, a notice of proposed rulemaking (NPRM) was published on part 575, "Consumer Information," proposing modification of the existing warning label required in multipurpose passenger vehicles (other than those which are passenger car derivatives) with a wheelbase of 110 inches or less advising drivers that the handling and maneuvering characteristics of these vehicles require special driving practices.

### Consumer Programs

- On September 3, 1996, in response to petitions for rulemaking, a request for comments was published on part 583, "Automotive Parts Content Labeling,"

## Canada

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**Nicole Pageot**

Transport Canada

Just in case you've lost count, this is the thirteenth—but last—status report you'll be hearing today. By now, our glowing accounts of past achievements and future plans for improving road safety have no doubt begun to blur in your minds. Yes, I'm about to give you yet another overview of accomplishments and renewed goals—this time for Canada.

Canada is a large country—about 9.2 million square kilometers in area—with a small population—30,000,000 people—concentrated mainly near the southern border. Its economy relies heavily on a large network of highways, about 900,000 kilometers in length.

It's been over 25 years since Canada first began to regulate road safety at the federal level and, in that time, traffic-related deaths have decreased by almost 50%. Much of this reduction can be attributed to the increased use of restraint systems—which is to say, seat belts, infant restraint systems, child restraint systems, and booster cushions. According to a 1997 survey conducted by Transport Canada, the rate of seat belt use for drivers of light-duty vehicles in Canada is over 90%. And, the proper use of child restraint systems is 76%, which represents an increase of 18% over the rate observed in 1989.

While we're very pleased with these statistics, we plan to do more—particularly with regard to infant and child restraint systems. The federal government is continuing to work in conjunction with the provinces, manufacturers, and all members of the road safety community to increase the use of infant and child restraint systems. In addition, we're working to improve their design. Our restraint systems are already among the safest in the world—they must meet strict performance requirements; tether anchorages are mandatory in all passenger cars; and as of September of the year 2000, tether anchorages will also be required in minivans, sport utility vehicles, and light trucks. However, a problem remains with regard to the correct installation of infant and child restraint systems, which we're attempting to address by conducting research to make these devices more user friendly.

At the last ESV Conference, we reported our intention to revise Canada's occupant protection requirements, and last year, we published a new regulation that sets more stringent head and chest protection criteria. In an attempt to further improve occupant protection, we've also been studying air bag performance—in particular the requirements of people

who are short in stature. Over the past two years, we've conducted over 50 full-scale crash tests and close to 100 static air bag deployments, using fifth percentile female test dummies and 6-year-old Hybrid III test dummies. The purpose of most of this research, which was performed in conjunction with NHTSA, was to assess the feasibility of introducing a new offset frontal crash test. The proposed test is conducted at moderate speed, with the seats in the full forward position, using two fifth percentile female Hybrid III dummies. Dainius Dalmotas will be presenting the results of this research later in the week. As part of our assessment of air bag performance, we also examined data collected under our program of in-depth investigations of real-world collisions. The data showed clearly that first-generation air bag systems were overly aggressive to belted occupants, causing them unnecessary injuries. This problem was brought to the attention of vehicle manufacturers, who responded by introducing depowered air bag systems in the vehicles sold in Canada. We are in the process of evaluating the effectiveness of the second generation of air bags through a study of crashes involving late-model vehicles in which an air bag deployed. Preliminary results from this study will also be presented later in the week.

Although we've made, what I consider to be, excellent progress in reducing the injuries and deaths due to motor vehicle collisions, we're always looking for new ways to improve road safety. If significant further progress is to be made, I believe it will come through improvements in side impact protection. To this end, Transport Canada has been conducting research on several fronts to help establish the basis for a reliable test of side impact protection.

As part of this research, we've systematically measured and compared the responses of the different side impact dummies that are currently available, which include the US SID, the EuroSID I, the BioSID, and—the new woman on the block—the SID-II. We've also been studying how well the vehicle damage patterns produced by different deformable barriers match the damage patterns observed in 100 real-world crashes. At the same time, we're comparing the injuries sustained in these crashes with the test dummy responses. Because the validity of a side impact compliance test will depend to a great extent on the biofidelity of the dummy used, Transport Canada is also participating with both the International

Harmonization Research Activities and the International Standards Organization in the development of what we hope will be the first internationally accepted side impact dummy—the WorldSID.

So far, it may appear that much of our effort over the past two years has gone into improving occupant protection. While this is true, we're also involved in a number of other interesting initiatives.

The increasing popularity of minivans, sport utility vehicles, and light trucks has led to concern about the fact that, in a collision between these larger vehicles and passenger cars, it is usually the occupants of the smaller vehicle who are injured. One important future project is to document the damage and injuries sustained in such collisions as a first step to developing a regulatory means of minimizing the injuries that are caused. The safe transportation of children to and from school has always been a high priority for Transport Canada and, over the years, we've implemented a number of safety standards specific to school buses. Although very few children are seriously injured in collisions while they are *inside* the school bus, children are still being injured by the school bus once they have disembarked. In order to improve visibility around the bus for the driver, we have recently revised our standard governing exterior mirrors in order to reduce blind spots to a minimum. These new requirements are unique to Canada.

When we first proposed to revise our occupant protection regulation, we included requirements to minimize the risk of seat-belt-induced injury. Originally, we intended to prescribe seat belt anchorage location zones using a device called the Belt-Fit Test Device, or BTDF for short. In the end, we did not introduce the seat-belt fit requirements. Instead, a collaborative research program was set up with industry to develop an electronic version of the BTDF that is to be used with Computer Assisted Design tools early in the design cycle. The research group has conducted preliminary validation trials comparing the performance of the physical device with the computerized version, and the results have been promising. We are especially excited by this project as the electronic BTDF is a prime candidate for electronic compliance, which we hope to use more frequently in the future.

Another initiative we've undertaken attempts to explore why anti-lock braking systems have not reduced motor vehicle collisions as much as we expected. The potential of ABS to reduce collisions by improving driver control has been well documented in

controlled testing environments. However, it appears that, while ABS has significantly reduced the number of multiple-vehicle collisions, there has been an increase in single vehicle collisions. We're currently studying the reasons for this unanticipated result by trying to evaluate whether drivers understand how ABS works, whether it is being used properly or not, whether anti-lock braking systems encourage risky driving behaviour, or whether a combination of these or other factors may be responsible.

We're also conducting research into providing protection to lighter vehicles that are involved in collisions with heavy vehicles—with a view to introducing heavy vehicle underride protection requirements. In a related initiative, Transport Canada is leading the development of comprehensive North American regulations for cargo security, in conjunction with the U.S. Federal Highway Administration, the Canadian Provinces, and the private sector.

In addition to our other efforts, we've also been active in the domain of Intelligent Transportation Systems, or ITS. Much of our recent work in this area has focused on leading the International Harmonization Research Activities working group, which is developing procedures for evaluating the safety of in-vehicle information, control, and communications systems.

We're also studying whether the use of cellular telephones while driving is a safety hazard. We've just completed the data collection phase using Transport Canada's Quality of Driving evaluation procedure.

Last year, we also conducted a study of behavioural adaptation to Fatigue Warning Systems. Although the preliminary results of the study provided no evidence of behavioural adaptation, the warning signals triggered by significant drowsiness had no observable effects on drivers. The results of this study underscore dramatically the need for systematic research into how human beings respond to new technologies. In this regard, the theme of the Conference, which highlights the human factor, is especially appropriate, and we are pleased to see that increasing attention is being paid to this area.

Details of much of the work I've touched on here will be presented at greater length in papers at the technical sessions, in posters, and in our display in the Exhibition Hall.

I hope you will enjoy your stay in Windsor, and I look forward to meeting you during the course of the week.

# Invited Speakers Executive Panel

## Trends and Priorities in Motor Vehicle Safety for the 21<sup>st</sup> Century

Moderator: Gerard J.M. Meekel, Ministry of Transport, The Netherlands

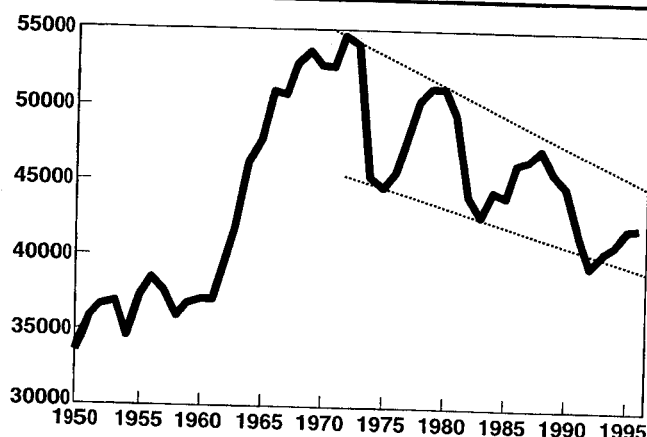
### United States

**Philip R. Recht**

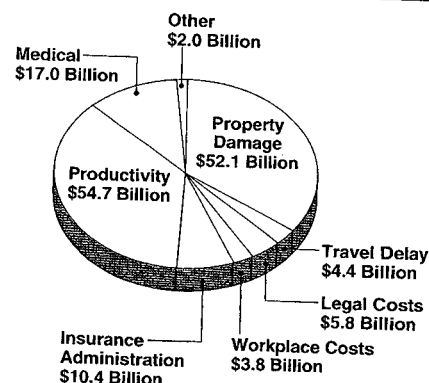
National Highway Traffic Safety Administration

Oral Presentation presented at the Conference.

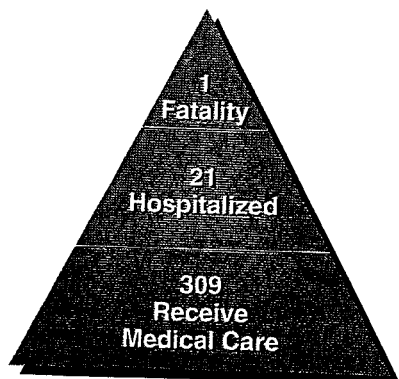
### Motor Vehicle Fatalities in the U.S.



### Societal Costs of Motor Vehicle Crashes Total \$150.5 Billion



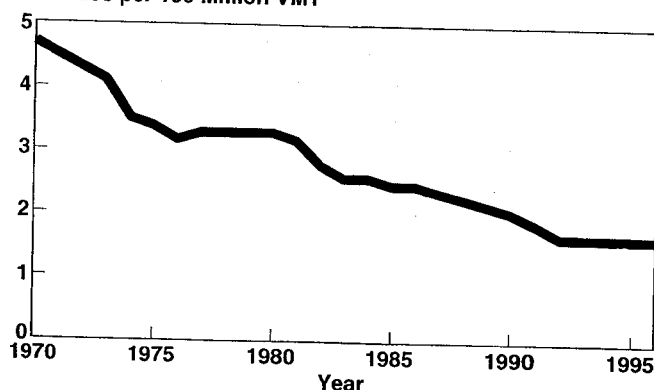
### Injury Pyramid



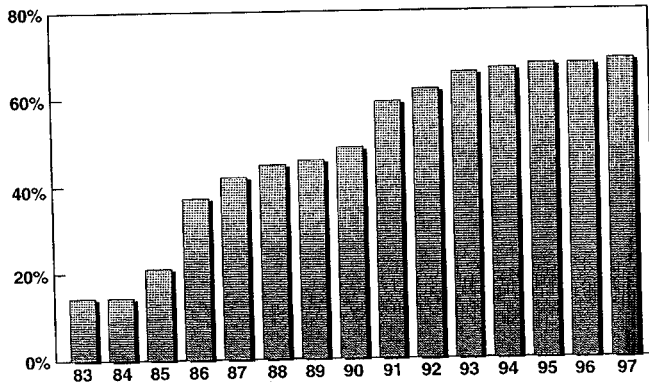
1996, Nat'l Center for Health Statistics

### Fatality Rate

Fatalities per 100 Million VMT

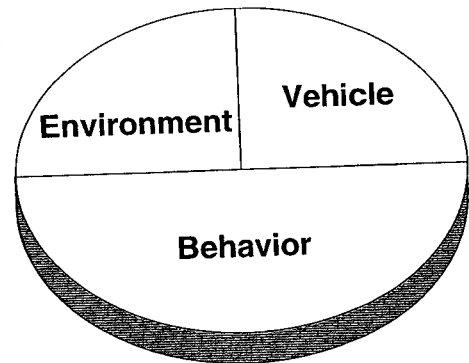


## U.S. Seat Belt Use Rates

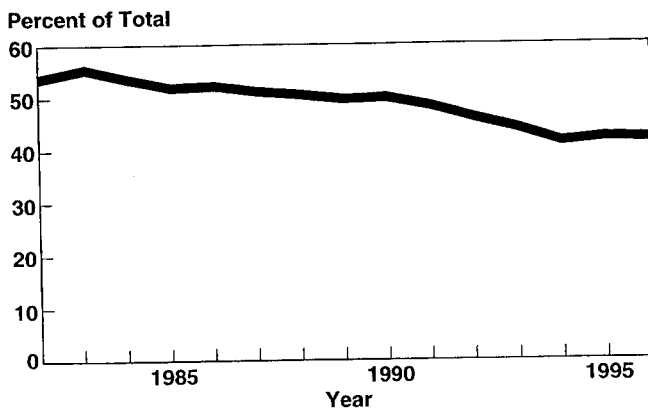


1983-1990 from 19-city survey  
1991-1997 from State surveys

## Opportunities



## Alcohol Related Fatalities



## Environmental Priorities

- Rail Crossing Improvements
- Highway Design Upgrades
- Congestion Reduction
- Motor Carrier Safety Improvements

## Factors and Challenges

- Diminishing Returns on Vehicle Side
- Harder to Get Returns on Behavioral Side
- Increased Exposure
- More Younger and Older Drivers
- State and Local Enforcement Levels Declining
- Speed Limit Increases
- Aggressive Driving
- Air Bag Risks
- Vehicle Mix Changes
- Additional Distractions
- Globalization of Economy/Emerging Nations
- Need for Emission Improvements/New Technologies

## Vehicle Priorities

- Improved Frontal & Side Protection
  - Improved Restraints
  - Crash Energy Management
- Improved Rollover Protection
  - Enhanced Stability
  - Occupant Protection
- Intelligent Transportation Systems (ITS)
  - Crash Avoidance
  - Automatic Collision Notification
- Consumer Information
- New Technologies and Materials
- International Harmonization

## **Behavioral Priorities**

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- **Occupant Protection**
  - Adult Belt Use
  - CRS Use
  - Kids in Back Seat
- **Impaired Drivers**
  - .08 BAC
  - Repeat Offenders
- **Enhanced Enforcement**
  - Suspended Licensees
  - Aggressive Drivers
  - Automation

## **Behavioral Priorities**

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*(continued)*

- **Older and Younger Drivers**
  - Screening
  - Licensing
  - Education
- **Other Issues**
  - Fatigue
  - Distractions

## **Benefits of Harmonized Research and Regulations**

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- **Improved Safety**
- **Efficiencies of Research/Cost Savings to Governments**
- **Cost Savings to Consumers**

## **NHTSA Guiding Principles**

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- **Maintain or Improve Safety**
- **Open Process / Retain Sovereignty**

## **NHTSA Activities – Research**

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- **IHRA**
  - Began in 1996
  - Identified Five Research Areas
    - Advanced Offset Frontal Crash Protection (EC)
    - Biomechanics (US)
    - Vehicle Compatibility (EC)
    - Pedestrian Safety (Japan)
    - Intelligent Transportation System (Canada)
- **Other Area of Cooperative Research**
  - Functional Equivalence (US / Australia)
- **Potential Future IHRA Topic – Side Impact Protection**

## **NHTSA Activities – Rulemaking**

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- **Regional (NAFTA, APEC)**
- **Worldwide (WP.29)**
  - Global Agreement
  - To Be Open for Signature  
June 25, 1998



## **Principal Elements of the Global Agreement**

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- Open to All UN Members
- Compendium of Candidate Technical Regulations
- Global Registry (Consensus Voting)
- Transparency
- Tiered Harmonization
- Sovereignty Preserved
- Obligations

## **Challenges to International Harmonization Activities**

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- Different Safety Environments
- Sovereignty Needs to be Preserved
- Perception of Safety Degradation
- Ensuring an Open and Fair Process

Kazuyoshi Matsumoto  
Ministry of Transport

## IN THE 21<sup>ST</sup> CENTURY

In the 21<sup>st</sup> Century we will see motor vehicle usage spread throughout the world, with more and more drivers joining the traffic. People will be concerned more about safety, and willingly pay the costs for safety. Governments will be asked to carry out needed regulations, and manufacturers asked to actively improve the safety of vehicles. Crash worthiness will continue as an important issue.

## TECHNOLOGICAL TRENDS AND SAFETY

### SMART VEHICLES

Smart Vehicles have become popular and we have seen great impact on traffic control, safety, and navigation. In Smart Vehicles the Central Processing Units (CPUs) integrate various sensors and actuators,

process data, communicate outside of the vehicle, and determine and control the vehicle.

The **Advanced Vehicle Control and Safety System (AVCSS)** in the U.S. and the **Advanced Safety Vehicle (ASV)** in Japan are similar in the field of automotive technology.

Figure 1. below shows the ASV Road Vehicle Communication/Intervehicle Communication System. These advances are examples of technological trends in the fields of:

- I. Preventive Safety
- II. Accident Avoidance
- III. Autonomous Driving
- IV. Damage Mitigation
- V. Post-collision Injury Mitigation & Prevention
- VI. Fundamental Technology

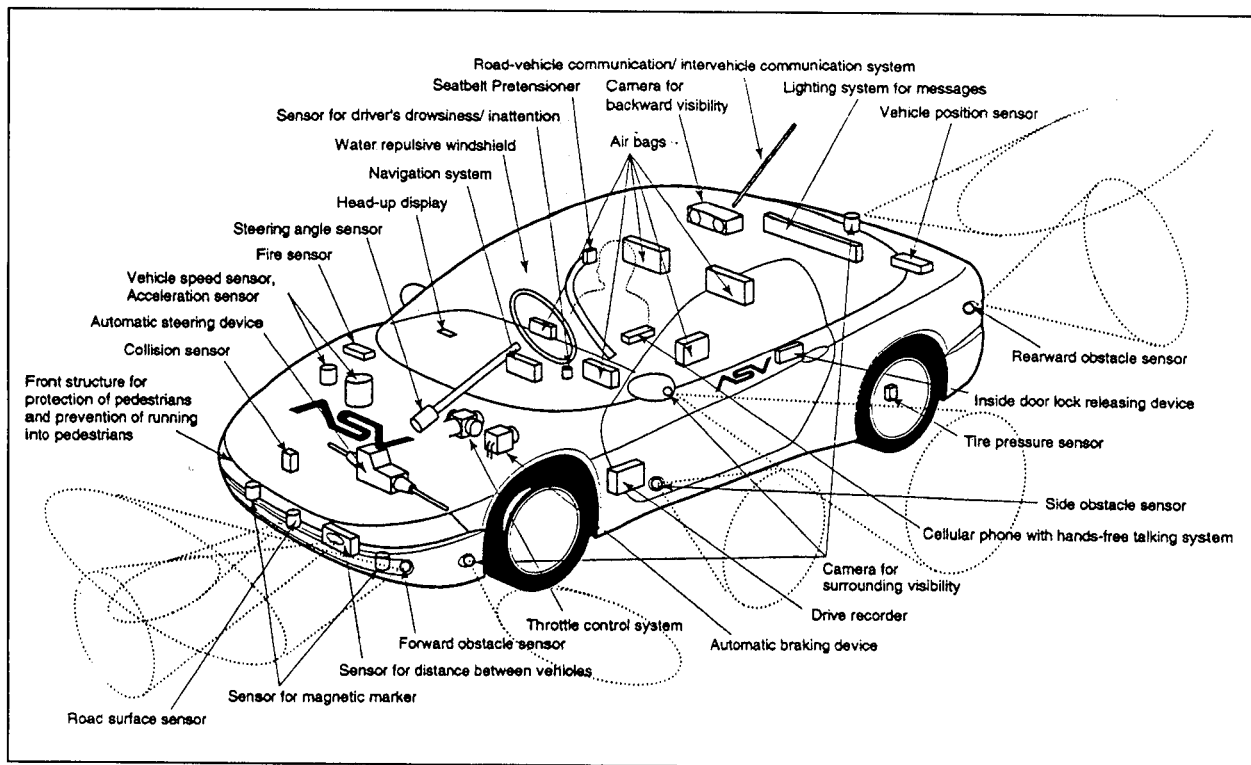
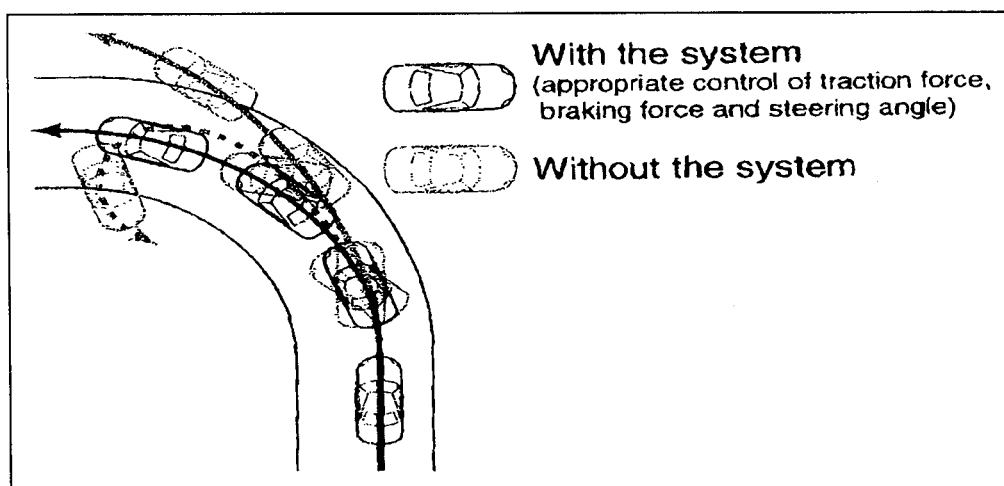


Figure 1. Road -Vehicle Communication/Intervehicle Communication System

An example of a Smart Vehicle component is the **Dynamic Stability Control System**. The System controls the traction force, the braking force and the steering angle, and keeps the vehicle stable depending on the road surface, wheel loads, etc.

The necessary data to control such actions are acquired from within the vehicle, from roadside facilities, or from satellites. The stability control of an automobile with and without the System is demonstrated in Figure 2. below.



**Figure 2. Dynamic Stability Control System**

#### **Fail Safe**

In failure, the Smart Vehicle becomes a conventional vehicle and the driver may not be able to respond properly. Non-failure is required, and for practical purposes, multiple systems should be equipped. Regulatory authorities will be concerned about to what extent the multiplicity is required for CPUs.

#### **Human Related Factors**

**With regard to human related factors, the following should be researched and determined:**

- Timing and level of system intervention
- Necessity of informing the driver of the intervention
- Method and frequency of information

**Out of above the following can be determined:**

- What should be regulated and how
- What should be standardized
- What is left to free design

There must be proper understanding of the purpose and limitations of the system.

#### **DRIVE RECORDER**

A drive recorder records the data from each sensor and overwrites old data. With the appropriate algorithms to detect abnormal activity, it preserves vehicle data during that activity. The drive recorder makes it possible to obtain accurate reproduction and analysis of accidents, and near misses.

**With the Drive Recorder we can determine:**

- What sort of movement the vehicle was making
- What sort of action each system was undertaking, and
- What sort of action (operation) the driver was taking

A Drive Recorder can make great contributions to traffic safety, particularly to improving vehicle structure and equipment.

**What needs to be resolved:**

- How the driver's privacy should be protected
- Who should be charged the extra expense of the recorder
- Who will have access to the data and to what extent

Meanwhile, transport businesses may adopt driver recorders for the sake of fleet control. People may volunteer to have the new technology if certain incentives are provided. In order to facilitate a broad application to safety measures, it is necessary to establish an official framework (law, regulations, etc.) that coordinate matters that need resolution.

### **GLOBALIZATION**

Company to company alliances, and mergers across the borders will result in giant companies with a global reach. Common structure, parts and equipment will be adopted across types and manufacturers. Governments will need to form alliances.

### **Defects**

Common use in large scale of parts, etc., may lead to large scale defects. Safety measures in the

marketplace should be reinforced---Governments should work in close cooperation.

### **Harmonization of Regulations**

Alliances should be formed to assure the harmonization of regulations. Existing regulations should be harmonized, and new regulations should be developed under cooperation from the very upstream stages of research.

The UN/ECE/WP29, and International Harmonized Research Activities (IHRA) under the auspices of the International Technical Conference on the Enhanced Safety of Vehicles of (ESV) are the front-runners.

To make the best use of the limited resources in this field, various activities throughout the world should be aligned in cooperation to one main flow.

Note: This paper is a summation of a slide presentation given by Mr. Kazuyoshi Matsumoto. Apologies are offered where summation is not exact.

## France

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**Christian Steyer**  
Renault SA

### Priorities in Motor Vehicle Safety for the 21st century

The potential of improvement for safety is still extremely important. The only socially acceptable target is to look for zero killed and severely injured on the roads. A few figures from the French accident research show the potentials. Going from 70 % to 100 % safety belt wear rate could reduce fatalities in cars from one third. In more than half of the deadly accidents alcohol or excessive speed is a direct cause. Those three factors, safety belt, alcohol and speed are directly related to the driver's behaviour and I am convinced that changing the way the driver considers driving is certainly the first source of progress for safety. This has of course a lot to do with political decisions. Nevertheless there are some technological and regulation issues that can also influence the situation for both passive and active safety.

In the area of passive safety, the protection of cars in case of an accident has improved on a significant way over the last 10 years. We can estimate that the front crash protection in a modern car at 60 km/h against a rigid wall is equivalent to that of a car of the late 80s at a speed of 50 km/h. This is due to a very important progress of the restraint systems with the generalisation of belt pretensioners, load limiters and of course the new airbags that are optimised to work in an optimal way with the safety belt. Over the next years the side airbags protecting both the thorax and head will generalise with the same benefits as the frontal airbags. The car to car compatibility is also a very important topic that has to be addressed on short turn.

The next generation of systems will have a lot of adaptation possibilities with multi level airbags or pretensioners. More generally, the protection technology already offers a great potential to adapt the system both to the person to protect and to the crash situation. However, the major issue is to succeed in having reliable tools to identify the occupant and the kind of crash. For instance, the tolerance level of the individual is strongly related to the age. Not having that information available greatly limits the adaptation possibilities of a safety system. Another important issue is the crash severity and how reliable a very early detection of a crash violence can be. The limits of intelligent systems will really be the capacity to feed them with relevant data. We will certainly see the emergence of new links between the active and passive

safety systems. As an example, the stability control system of a car can provide information on the pre-crash conditions like the transversal speed in case of a side impact. Other links can of course be done with navigation systems: knowing exactly on which kind of road you are driving can be useful to evaluate the probability of a situation. On another hand, you know how important the rescue time can be. The car is already able to call for help in case of an accident indicating very precisely the location, Renault has already developed a first simple emergency call system. The next generations will give information on the kind of crash, the number of occupants and enable a better tuning of the rescue forces required.

As concerns active safety, there will certainly be a new revolution in the next 10 to 20 years. The next generation of systems will enable you to change completely the behaviour of the car by acting on the engine power, the brakes and the steering system. This can be used on two very different ways. The first way is to take the place of the driver and push the limits of the driving possibilities of the car. This can be very exciting but will be also very dangerous, as because the driver will lose information on the physical limits of the car and once he reaches those limits, he will not be able to control the situation anymore. The second way of using stability controls is to automatically bring back the car into a safe drivability area. This will for instance brake the car when it comes close to the limits instead of correcting the behaviour of the car to be able to go faster. The choice that will be made by the car manufacturers between those two philosophies will have a direct influence on the real world safety and the number of accidents.

Another part of active safety is related to the analysis of the driver's attention and tasks and the crash avoidance measures. In that area also, the short term prospects are worrying. Everybody knows about the statistics of accidents due to the use of mobile phones while driving. All the new communication and navigation systems may turn the attention of the driver from his main activity - driving. Of course, you can imagine very smart and efficient man/machine interfaces but the attention potential of the driver is limited. We have to be very cautious because any task that requires some attention can become dangerous even if you use a vocal interface for instance. A lot of research has to be done in that area to understand where the limits of a dangerous situation are. This is

also a matter of training and may be in 20 years, being able to communicate while driving will be taught before new drivers get their driving license.

Of course, the technology is only one dimension of the safety related problems. The regulation process is a key issue to control and generalise the progress made by the car industry. At the age of globalisation, it is not possible to imagine that the car industry stays with as many local regulations addressing the same safety questions as today. Why should the safety of a car in side impact be tested on two different ways with two different procedures and dummies on both sides of the Atlantic. In that area, the Global parallel Agreement is a very important working frame to develop world-wide regulations. This new regulation process should integrate the best of each regional regulation and promote common testing protocols in all areas. Local adjustments should be done if motivated by accidentological considerations on the existing vehicles, road infrastructure or driving habits. This process is going to take time but Renault, as a global company supports it. The only important thing to preserve is the necessary reactivity in order to adapt regulation to the technological progress. We have in Europe a specific procedure 8.2.c of the 'Reception Directive of vehicles 70/156/CEE' that enables a country to propose some derogation for a new device improving safety. This derogation is going under the condition of a corresponding further regulation change. This kind of procedure was used recently after a Renault initiative to introduce a new generation of safety belts designed to work with an airbag and reducing strongly the risk of thoracic injuries. This new system did not comply with one of the regulations on safety belts. Nevertheless, we

could introduce it by demonstrating its efficiency and proposing an alternative evaluation procedure.

I would like to conclude by insisting also on the importance of the political decisions. The car industry is highly competitive and the manufacturers have to offer what the clients expect. It is very difficult for a company to restrict the freedom of the driver from its own initiative. I said in my introduction that the most efficient safety measure would be to reach a 100% seat belt rate. It is very easy to equip the cars with a system that won't start the engine unless the safety belt is fastened. That kind of measure can only be taken by the political power. It has to do with the vision of society, maybe in some cases it should even be decided on a democratic way. The car industry has an important role to play by proposing new solutions to improve safety. The research on accident causes with a very global view is absolutely fundamental. We need to have a thorough understanding of what happened on a large statistical scale to be able to evaluate the efficiency of new devices. An accident is most often a coincidence between a lot of factors. There is not one unique cause but several causes involving man, the vehicle and the infrastructure. In some cases like the pedestrian protection, the most efficient means to progress is probable to invest in the infrastructure and prevention rather than changing completely the design of the cars. In any case, the best possible cost / advantage ratio and the delay needed to see the positive effects of a measure should always be considered by the political power to make the right choices.

## United States

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**Richard L. Klimisch, Ph.D.**

American Automobile Manufacturers Association

### Overall Trends and Priorities

*Figure 1* is a version of the familiar Haddon matrix which indicates that the primary emphasis of traffic safety in recent years has been to improve the crashworthiness of vehicles, i.e. the vehicle-crash cell. It goes without saying that such vehicle improvements will continue but it is widely recognized that the future gains from this approach will be limited. Therefore, the major priority for motor vehicle safety must be to broaden the focus if we are to continue to make significant improvements in motor vehicle safety. There also appears to be general agreement that the top left hand cell, the precrash-driver cell, has the most potential to reduce traffic fatalities and injuries in the near term. Actions included in this cell require changing the behavior of drivers (and passengers). The difficulty of changing behavior, especially long standing behavior, is often underestimated, even when the person knows the behavior is dangerous (smoking for example).

Three behavior change opportunities with the most potential for short term improvements are seat belt use, alcohol/drug use and aggressive driving. We have the most experience with programs aimed at increasing seat belt use rates. The most effective approaches to increase belt use are education and enforcement. Most of us prefer the education approach but such programs have not been able to achieve the desired high levels (90%) of seat belt use. Apparently, only strong enforcement programs can achieve such high levels. One characteristic of these programs is that the occupants whose behavior is easiest to change are those at the least risk and vice versa. That means that the biggest improvements are the hardest to come by and that is why the industry has been so active in programs aimed at passing standard (or primary) enforcement seat belt use laws (now called standard enforcement, i.e. police are able to stop vehicles solely because the occupants are not wearing safety belts). Most states in the U.S. have secondary enforcement programs in which vehicles cannot be stopped unless there is some other violation.

The conclusion is that for a priority ordering based on reducing fatalities and injuries, behavioral

changes are more important than technological changes to the vehicle. Based on a variety of sources, it appears that the opportunity for improvements through behavioral change are at least ten times larger than those for vehicle technological changes.

### Safety Trade-Offs

Another way to look at priorities relates to which occupants are being protected. This is particularly relevant because it recently became clear that the U.S. approach to regulation of air bags put children and other vulnerable occupants at risk in order to protect occupants who flaunted the law by refusing to wear safety belts. When the reality of this unintended consequence became apparent, the rules were changed quickly. This begs the question as to what the priorities ought to be. An answer to this question and to other related questions is contained in *Attachment 1* which is the "Joint Statement and Recommendations on Advanced Air Bag Technology," put together in March of 1998 by the American Automobile Manufacturers Association, the American International Automotive Manufacturers, the Automotive Occupant Restraints Council and the Insurance Institute for Highway Safety. The priority suggested therein is: "First, priority should be placed on improving protection for belted occupants while reducing the potential for harm to children and other occupants who are out of position. Our goal is to do no incremental harm to out-of-position occupants. Second, priority should be directed to improve protection for unbelted occupants, to the extent consistent with the first priority."

The above issue demonstrates one of the trade-offs inherent with restraint systems. Such trade-offs must always be dealt with. Some suggest that technology will allow us to avoid such trade-offs but that is totally unrealistic. In fact, the vehicle designer is faced with a large number of trade-offs. One that will undoubtedly be inescapable in future is the trade-off between environmental considerations and safety considerations. Great emphasis is being placed on improving fuel economy in future vehicles. For example, the European industry has recently offered to make major improvements in fuel economy in the

coming decade. Similar commitments have been made by the Japanese automotive industry and pressures are expected to increase in the U.S. for additional improvements in fuel efficiency, especially in light of the recent Kyoto Agreement on Global Climate change. These pressures to increase fuel efficiency will almost certainly cause manufacturers to reduce vehicle weight because that is the most direct way to increase vehicle fuel efficiency. It is equally certain that these weight reductions will have an adverse effect on safety as demonstrated by Evans et al. Similarly, it has been estimated that the weight reductions of CAFÉ (Corporate Average Fuel Economy) regulations in the U.S. more than offset the positive safety impacts of air bags. Finding ways to offset the safety deficits of weight reductions will present a significant challenge to the traffic safety community in the years ahead.

### Technological Changes

There are many technological changes being introduced into vehicles, e.g., advanced restraints, intelligent vehicle systems, electronic stability control, etc. Regarding intelligent vehicle systems, it would appear that the time is ripe for information but we're not quite ready for intervention. It goes without saying, that such devices also have many tradeoffs including safety tradeoffs.

Because of recent issues about inflation induced injuries by air bags, there has been increased interest in providing sensors that are able to adjust inflation energy or to suppress the air bag altogether if the occupant is out of position or is an infant or vulnerable in some other way. *Attachment 1* discusses regulations and development of such advanced air bag systems. Although we are always looking for a silver bullet, the process will more likely be evolutionary rather than revolutionary. It is also important that the process be driven by data so as to minimize unintended consequences.

### Harmonization

Industry is firmly convinced that harmonization benefits everyone and will help optimize safety and environmental systems on a global basis. On the other hand, trade barriers including non-tariff trade barriers lower standards of living for everyone. Clearly, harmonized regulations must be stringent and performance based (as opposed to design-based) and they must be cost effective. It is also crucial that the harmonized regulations be cost effective. If all these

conditions are fulfilled then we can be sure that harmonization will indeed improve safety.

Unfortunately, there has been a great deal of negative reaction to the concept of functional equivalency ... and apparently the IHRA activity in this regard has been deactivated. This is unfortunate because it is essential that a methodology be developed for comparing stringency of regulations. It is certain that the first question that will be asked about a proposed harmonized regulation will be: how does it compare to the existing national regulation. It is not realistic to expect regulators to allow stringency to be sacrificed for the sake of harmonization and we must have an accepted methodology to compare stringency.

There are a number of initiatives underway which are directed at harmonization. One of the most important was initiated at the last ESV in Australia, i.e., the International Harmonized Research Activity. It is hoped that this activity will help avoid unharmonized standards in the future. We think it is important to have industry as a full partner with government in the IHRA activities.

WP29 (Working Party 29 of the Inland Transport Committee, Economic Commission of Europe, United Nations) is rapidly becoming the global forum for harmonized standards, especially since the signing of the new Global Agreement (often called the "Parallel Agreement") in Geneva in June of 1998. Actually, WP29 has already developed a number of regulations that approach global harmonization. However, progress has been slow and there are a large number (ca. 100) of existing regulations that have to be harmonized.

### Europeanization or Americanization

One of the widespread humorisms is that the U.S. EPA is in favor of harmonization as long as all the other countries adopt U.S. EPA regulations. Similar statements have often been expressed regarding European regulations. Harmonization in this way will give manufacturers in the country whose regulations are adopted an advantage over those in other countries, especially if harmonization results in the predominant adoption of regulations from one jurisdiction. Until the present, the WP29 has been primarily a European forum and the rules developed there have primarily been utilized in Europe; in fact, the forum is currently dominated by European countries in terms of committee chairs, etc. There has been an underlying



concern that harmonization through this forum would simply involve a process in which all countries would adopt European regulations. Since WP29 is part of the Economic Commission of Europe, it is important to do whatever is necessary to give it more of the appearance of the global forum that it has become. For harmonization to be successful, it must not be seen as either a Europeanization or, for that matter, an Americanization of regulations.

#### Priorities for Harmonization

From an industry point of view, the most important aspects of harmonization are the regulations themselves (including the test procedures). These are more important than the certification or mutual recognition processes which primarily involve the elimination of redundant testing and/or redundant bureaucracy. On the other hand, differences in the regulations would likely require physical modification of vehicle hardware. For regulations like crash standards the modifications could even involve basic structural elements of the vehicle which would likely be prohibitively expensive. Since the new Parallel Agreement seeks to harmonize regulations, it is of great value. On the other hand, after the regulations and test procedures are harmonized industry's next priorities will be certification and mutual recognition as our ultimate aim is to be able to manufacture vehicles that can be "tested once and accepted everywhere."

#### Compatibility.. *More Than Bumper Height*

There has been a great deal of publicity in recent months about the danger presented by light duty trucks crashing into the sides of small cars. The ratio of fatalities in the truck versus the small car shows that the passengers in small car's are at much greater risk than those in the light trucks for such crashes. Such so-

called "compatibility problems" have been with us for a long time. (An even more striking example is the situation in which heavy-duty trucks crash into small cars.) It has been suggested that adjusting bumper height could serve to reduce this incompatibility. Tests presented at this meeting suggest that this approach is erroneous. It should be pointed out that there is both a numerator and a denominator in this ratio. The light trucks clearly provide superior protection for occupants. The side impact tests presented at this meeting by GM indicate that the Mercedes Benz M-Class is not superior with respect to compatibility than cars with higher bumpers and it appears that it is primarily a question of weight which determines the outcome in such crashes.

#### Summary

There are many ways to consider priorities. Overall, it is clear that the focus on vehicle crashworthiness must be broadened if we are to continue the impressive progress in traffic safety. The area of highest potential appears to involve behavior changes related to seat belt use, alcohol and drug use. In order to achieve the desired results, the approach apparently must involve enforcement as well as education. Technological change will continue, but the largest benefits will come from the aforementioned behavioral changes.

Progress also continues in harmonization, and the IHRA plays an important part in this along with WP29. Major challenges remain to deal with the so-called compatibility problem and the weight reductions that will be required to improve fuel economy. Technological improvements will continue, but we must be constantly aware of the inevitable trade-offs in order to minimize unintended consequences.

Haddon Matrix Showing Historical Focus


	Driver	Vehicle	Environment
Pre-Crash			
Crash			
Post Crash			

Figure 1



American Automobile  
Manufacturers Association



Association of International  
Automobile Manufacturers, Inc.



Automotive Occupant  
Restraints Council



March 1998

### **Joint Statement and Recommendations on Advanced Air Bag Technology**

The following **consensus and recommendations** on advanced air bag technology were jointly developed by the American Automobile Manufacturers Association (AAMA), the Association of International Automobile Manufacturers (AIAM), the Automotive Occupant Restraints Council (AORC), and the Insurance Institute for Highway Safety (IIHS).

On January 20-21, 1998, representatives of the four organizations listed above and their member companies attended an advanced air bag technology workshop at the IIHS Vehicle Research Center in Ruckersville, Virginia. Air bag system engineers, vehicle design engineers and motor vehicle safety professionals met to review and assess the data relevant to current air bag performance and to discuss advanced air bag technology. The goals of the workshop were not only to review the progress of current and advanced air bag technology but to facilitate the rapid development of future air bag systems and to define consensus policy approaches to best achieve this goal.

As Dr. Ricardo Martinez, Administrator of the National Highway Traffic Safety Administration (NHTSA) said on February 4, 1998, "Seat belts are the single most important life-saving device in a motor vehicle." Air bag systems complement the safety performance of belts and the combination of belts and bags offers the highest level of occupant protection.

### **SUMMARY OF CONSENSUS AND RECOMMENDATIONS**

Occupant restraint systems in use today have been consistently improved and already incorporate a wide variety of technical features designed to reduce the risk of air bag inflation-related injuries, particularly to unrestrained and out-of-position occupants. These features have reduced many of the risks but new technologies are needed to reduce these risks even further. Therefore, the government, vehicle manufacturers, and air bag suppliers have been aggressively working to find additional means to reduce these risks while retaining the lifesaving and injury-reducing benefits that air bags already provide.

AAMA, AIAM, AORC, and IIHS recommend that future government and industry actions:

- **Continue support for educating the public on air bag and seat belt safety and for enacting and enforcing primary seat belt use laws.**
- **Establish priorities for occupant protection.**
- **Assure that future air bag rules are objective, practicable, meet the need for motor vehicle safety and are performance based and data-driven.**
- **Retain the current mid-size male, unbelted, high-speed sled test until other, more appropriate tests for assessing unbelted protection can be developed.**
- **Avoid arbitrary leadtimes and deadlines which may inadvertently inhibit innovation and result in unintended consequences.**
- **Undertake a thorough and timely real-world evaluation of the safety effects of depowering.**
- **Recognize that air bags are just one part of a vehicle's occupant protection system; that no single combination of air bag characteristics is best for all vehicles; and that as a result, attempts to "rate" vehicle performance on selected air bag design characteristics are misleading.**

## **BACKGROUND**

Air bags save lives – more than 2,700 to date – and will save an estimated 3,000 per year when all vehicles on the road have driver and passenger bags, according to NHTSA. Air bags also significantly reduce the risk of serious head injuries. However, out of more than two million air bag deployments to date, deployments in relatively low speed crashes reportedly have caused about 90 fatalities, including 51 children. Of the 39 children aged 1-9 years who died, 31 were totally unrestrained. The other eight (8) appear to not have been in restraints that were properly secured or appropriate for their size and age. There were also 12 fatal injuries to infants riding in rear-facing infant seats that were positioned in the front seat, contrary to warnings against such use. Almost all of these fatalities could have been avoided by proper restraint use and placement. The potential for serious injury from any air bag is greatest at initial deployment as the bag opens the cover and starts to inflate. Properly positioned and restrained occupants are highly unlikely to be within this zone.

## **CONSENSUS**

While technological improvements continue to be important, the most effective way to achieve immediate gains in safety is through increases in occupant restraint use – by having everyone properly restrained and positioned in a seat belt or child safety seat, and, whenever possible, by placing children 12 and under in the rear seat. Efforts must continue to educate the public and to enact and enforce effective legislation at the State level. These behavioral changes will provide the most immediate protection for the occupants of the more than 60 million vehicles with air bags now on the road.

Engineers from government, vehicle manufacturers, and air bag suppliers have been aggressively working, both individually and collectively, to find solutions to help further reduce the risk of serious injury from air bag deployments while retaining the significant benefits that air bags provide. Through their work, air bag technology has evolved substantially over the last 30 years.

A variety of technological features which can help reduce the risk of air bag-related injuries already exists in various combinations in today's air bag systems, based upon the unique design of each vehicle, including some or all of the following:

low force opening door covers, tethered bags, bag venting location and sizes, aspirated bags, bag tear seam configuration, bag fold patterns and geometry, advanced crash sensor technology, dual deployment thresholds based on safety belt use, recessed modules, child restraint identification for air bag suppression, and the reduction of inflator energy levels – the so-called “depowering” of air bags.

New designs in belt restraint systems are also available to work in conjunction with air bags and are being implemented as appropriate. These include:

belt pre-tensioners, load-limiters, advanced technology buckle switches, and variable load limiting retractors.

Most of these evolutionary technological improvements have been produced by suppliers and vehicle manufacturers absent any regulatory or legislative mandate. However, depowering required changes in federally-mandated test requirements to permit installation of the lower energy bags. This change came after a consensus statement by the technical community, similar to this document, after a meeting in Toronto, Canada, in November 1996 and an auto industry petition to NHTSA earlier that year. Following NHTSA's regulatory amendment in 1997, the technology was rapidly implemented – it is in most 1998 model year vehicles.

Cooperative efforts by government and the private sector have greatly increased public awareness of the facts associated with air bags and their proper use. Optimum air bag effectiveness is contingent upon proper restraint use and correct occupant positioning.

Further advanced technologies are being evaluated voluntarily and vigorously by automakers and the supplier industry in this highly competitive field. These include:

- crash sensor technology improvements to better predict the severity of the crash;
- occupant location sensors to detect the proximity of an occupant to the air bag module;
- occupant weight sensors; and
- new inflator technology that can vary inflator output, or new sensor technology that can suppress air bag deployment, depending on crash severity and/or occupant characteristics, such as belt use and occupant size and location.

Application of certain of these new and more complex technologies is expected to begin to be phased into selected passenger vehicles in the 1998 calendar year without a legislative or regulatory mandate.

It is important to note that the air bag system – with its sensors, inflators, bag designs and locations, and all the variations associated with those characteristics – is only one part of a vehicle's occupant protection system. Air bag systems must be uniquely configured to a vehicle's crash structural performance, interior design, and belt system. There is no single combination of these features that is "correct" for all vehicles. A combination of features that works well in one vehicle will not necessarily perform as well in another. Differing approaches are needed, depending on variables such as vehicle size, structural stiffness, steering column and instrument panel performance, type of belt, etc. Moreover, there can be more than one "correct" approach for a given vehicle.

And finally, to most effectively attain the benefits associated with air bags requires not only technology changes to vehicles but also changes to occupant behavior, especially having everyone properly belted and placing children in the rear seat. Efforts to educate the public, and enact and enforce effective legislation at the State level, must continue. While there is no opposition in principle to additional air bag regulation – some members of the technical community have already petitioned for this – such regulation needs to be carefully constructed so as not to stifle innovation or require technologies that still may have reliability concerns or unintended consequences.

## **RECOMMENDATIONS**

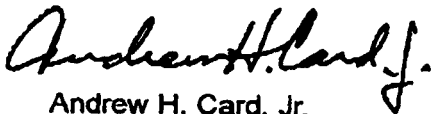
To achieve this, AAMA, AIAM, AORC, and IIHS recommend that:

- **Efforts must continue to educate the public on air bag and seat belt safety and to enact and enforce primary belt use laws.** Behavioral changes, including increasing seat belt use and securing children 12 and under in the rear seat, whenever possible, are essential to the effectiveness of air bag systems, regardless of which technologies are used. AAMA, AIAM, AORC, and IIHS will continue their efforts to achieve the Administration's goals in this area.
- **Priorities be established for occupant protection improvements.** Safety improvements, from brakes to air bags, never can maximize protection for all occupants in all situations and thus involve tradeoffs. To facilitate the design of advanced air bag technologies, we suggest the following regulatory priorities for improvement of occupant protection be established: First, priority should be placed on improving protection for belted occupants while reducing the potential for harm to children and other occupants who are out of position. Our goal is to do no incremental harm to out-of-position occupants. Second, priority should be directed to improve

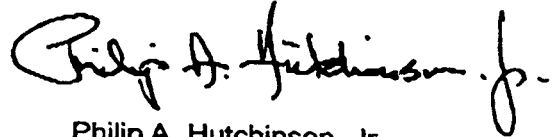
protection for unbelted occupants, to the extent consistent with the first priority. In no case should protection be diminished to any group as a result of rulemaking changes. Test protocols need to be developed which reflect these priorities.

- **Rulemaking on advanced air bag technology should be practicable, objective, meet the need for motor vehicle safety, and be performance-oriented and data driven.** Different emerging technologies will be appropriate for different vehicles. No promising approach should be precluded by technology-specific rules or rules not based on performance requirements derived from actual crash and laboratory data. Performance tests, new dummies, and associated injury criteria needed to measure the performance of advanced technology should be developed rapidly and jointly by industry and government.
- **The 30 mph mid-sized male, unbelted barrier test has resulted in less than optimum safety for unbelted occupants and, therefore, should not be automatically reinstated.** Data have shown that this test led to unnecessarily high air bag inflator energy levels. As a result, the sled test was allowed as an alternative to the unbelted barrier test, and this facilitated depowering. Changes in regulatory requirements, including elimination of the sled test alternative and a return to the barrier test, should only be made as a result of the rulemaking process described above.
- **Legislation specifying leadtimes, or other aspects, of advanced air bag technology is not necessary.** We believe market forces and the regulatory process are leading to introductions of phased advanced air bag technology that are designed to reduce the risk of air bag-related injuries. Rulemaking research must be thorough and rigorous, so as to promote the development of safe, reliable, and effective advanced air bag systems and to avoid unintended consequences. This requires that the process be open and transparent to all interested parties. Defining dates by which advanced technology is required could retard development of some promising technologies which might not be available by those dates. Manufacturers and suppliers have been working aggressively to accelerate the development of promising technologies.
- **NHTSA should make the real-world evaluation of vehicles with depowered air bags one of its highest priorities.** There is concern that the agency has not been able to devote sufficient resources to this issue. NHTSA should reallocate resources or seek the necessary additional funds from Congress to quickly and thoroughly evaluate the real-world performance of depowered air bags.

- The "rating" of air bags by comparisons of selected design characteristics would be meaningless and misleading. Air bag systems are only part of a vehicle's total, integrated occupant protection system, and they must be "tuned" to individual vehicles. Attempting to identify selected design attributes – such as whether an air bag is "vertically" or "horizontally" deploying – does not enable any meaningful comparisons of the systems in different vehicles.



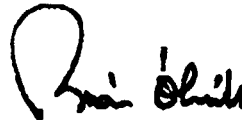
Andrew H. Card, Jr.  
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Philip A. Hutchinson, Jr.  
President  
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Automobile Manufacturers



Charles H. Pulley  
President  
Automotive Occupant  
Restraints Council



Brian O'Neill  
President  
Insurance Institute for  
Highway Safety



## Germany

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Josef Haberl  
BMW AG

I am pleased to be here and have the opportunity to discuss with you the future of motor vehicle safety. However, trying to predict the future, in my opinion, only is possible after one understands the present situation and, more importantly, how it evolved. Therefore, we need to look at the answers to a few questions before I give you some ideas on future needs with respect to motor vehicle safety:

**Why motor vehicle safety has become such an important issue?**

**What has been done so far to enhance motor vehicle safety?**

**What are the results of our efforts?**

Basically, there are only a few fundamental reasons why motor vehicle safety has become so important:

Of course, one obvious reason is the tremendous success of the automobile itself as the main means to fulfill the basic human need for individual mobility. Especially here in North America, where virtually everyone, from individuals to the entire nation, depends upon the availability of cars and trucks, surely no one can even imagine how our lives would be or how modern society would continue to function without, or even with a reduced availability of, motor vehicles.

The second is the increased prosperity of our society, which changed the pure need for mobility into a demand for safe mobility. Simply said, more and more people do not just want to drive, they increasingly ask for safer vehicles in a safer environment or, in short, for safer transportation. One could explain this with the statement that demand for safety in general increases with higher prosperity.

There is obviously another important effect that worked like a catalyst in contributing to this increased prominence of safety in the minds of the consumers:

The increased availability of consumer information programs about the safety of vehicles. Unlike other features such as comfort, styling, performance, which can be easily assessed by consumers on their own, the passive safety of a car cannot be directly determined and compared with that of another model. People have to rely either on manufacturers information or — what they obviously prefer — on independent crash test information like IIHS evaluations on crashworthiness.

Consequently, safety has become a fundamental requirement for most consumers when they are looking to buy a new car. Accordingly, manufacturers have reacted and continue to react to these requirements.

I am proud to say that it is BMW's philosophy on safety to — when ever possible — act, this means to always offer best possible technology to our customers. There are a number of good examples on that.

Having realized that safety is an important issue, the next main question is:

**What has been done so far to enhance motor vehicle safety?**

When I say motor vehicle safety it includes the following three areas:

- **The vehicle and its technology**
- **The environment or the road network and traffic control systems** and, of course,
- **All of us, the drivers**

Recognizing the greatest effect on road traffic safety could come from our own driving behavior and the environment, I do not want to address these areas in detail, today. As a representative of a vehicle manufacturer, I would like to use my short time to concentrate on vehicle technology. Let me begin with a short overview about what is already available:

Starting with **Active Safety**, that means technology which helps to avoid accidents, I would say that a big step forward was made in the past 10 to 20 years with **systems for a better vehicle handling** like antilock braking systems, automatic stability control, power steering and so on. In addition, progress was made in **comfort during driving**, an important factor for safer driving, as we all know. Many manufacturers at least offer such new active safety systems as an option, some of them — and BMW is one of these pioneers — have already made them standard equipment. Nevertheless, due to the tremendous progress in electronics, I believe we are far from the end of our possibilities in the Active Safety area. I will address this further, later on.

Regarding **Passive Safety** for passenger cars, extreme progress has been made in the past 10 years especially in the area of **body in white crash performance, friendly interior trim, advanced safety belt systems, airbags for frontal and side impact protection** and, last but not least, **fuel system**

**integrity.**

The increased use of computer simulation of crash tests resulted in very efficient crash energy management in the body structure to reduce dangerous intrusion into the occupant compartment even in high speed offset crashes like IIHS and EURO NCAP are performing. Excellent examples are the recent test results of cars like the BMW 528i, the Lexus LS400 and, even in the smaller car range, the new VW beetle.

Safety belts were made more effective by adding improvements like seat integration, height adjusters, pretensioners and loadlimiters.

Airbags for frontal protection have become standard in most countries, even without any regulation. And now, manufacturers are working on further improving the performance of these systems by integrating smart airbag technologies.

With more intelligent sensor technology, even side impact protection airbags started to enter the market. Just as an example, the new head protection system and thorax side impact airbag are standard in every BMW car.

This kind of technology may be able to address some of the concerns raised by aggressivity/compatibility issues.

So, a lot has been done already. Let's move onto:

**What was the effect of introducing this new vehicle safety technology? Does it really payoff?**

For BMW, I can confirm a very positive effect of our new safety technology because most of it already shows results in our own accident analysis. For example, we have seen a significant reduction in severe and fatal injuries in frontal impacts after the introduction of frontal airbags.

As we expected, even our new side impact head protection system, just introduced in 1997, has proved its superior potential for injury prevention in a few severe side impact accidents.

But these are only anecdotal examples. For a general answer to the benefit question, a short look in the overall accident statistics can provide us some more useful information:

The German Road Traffic Fatalities Statistics show a very positive continuous downward trend since the early 70's. The German safety experts relate this result, besides others, especially to the rather high belt usage rate, which was mainly achieved by the early introduction of mandatory safety belt use laws together with efficient enforcement.

Nevertheless, when we look at the total number of fatalities in US, Europe and Japan in 1996, a total of almost 100,000 lost lives, it gives one clear message to all of us involved in road traffic safety:

**We must reverse negative trends wherever they exist and reduce fatalities and severe injuries everywhere.**

This brings me back to the core question of the panel:

**What are the trends and priorities in motor vehicle safety for the next century?**

My first and most important answer is:

**All three traffic safety areas — the vehicle, the environment and the driver — must make contributions in a correlated way and**

**Areas with highest potential should be worked on with highest priority.**

As I already stated, it is my strong opinion that the most fatality and injury reduction potential is in the areas of the motor vehicle roadway infrastructure and our own driving behavior.

There are excellent examples in Germany for considerable improvement in accident rates with the introduction of intelligent traffic management systems. Such so called "electronically controlled flexible traffic signs" were set up on the highways around Munich in a cooperative program between BMW and the State of Bavaria. Since the introduction of these systems, a remarkable reduction in total accidents, seriously injured occupants and damage loss has been observed and has caused such systems to be permanently introduced on other highway sections.

Regarding the second area, our own driving behavior, I would like to mention the positive effect of education and, if necessary, legal requirements together with effective enforcement.

In Germany, authorities require a rather long driver education with mandatory training for specific higher risk events like night time autobahn driving before they accept an application for final examination.

In addition, it has been shown, time and time again, that higher safety belt usage rates can only be achieved by strong and efficient enforcement.

My strong plea for improvements in these non-vehicle related areas, of course, does not mean that the motor vehicle manufacturers do not want to further contribute to enhancement of road traffic safety. In fact, I assure you that we will continue researching, developing and introducing improved and new safety technology.

But, there is one clear message from customers that every vehicle manufacturer knows all too well:

**These technologies must remain affordable. Therefore, they must be based on sound analyses of real accident scenes, rather than, on politically-driven**

and sometimes even different and not globally harmonized regulations of the same issue.

In general, such a divergence in regulations does not have a benefit for our customers, but for sure will make the cars more expensive.

By the way, it is my personal opinion, that in the future, vehicle safety will be driven by competition much faster than regulations will ever be able to do so.

For BMW, I dare to say that we will derive further improvements in principle from existing knowledge and primarily from what we learn from our own and others accident analysis. Our so called HPS or side impact head protection system and the recently introduced safety battery connector are perfect examples for that.

As within the whole safety field, also within our responsibility, the motor vehicle safety, of course we should set priorities.

As already indicated at the beginning, for a further reduction of fatalities and severe injuries, I see more potential in the area of active safety than in passive safety.

It could be qualitatively described as follows:

1. Active safety systems (e.g. brakes, improved tires and steering) were available much earlier than passive safety technology, which entered production cars with first considerations of safety passenger cell and crumple zones as well as safety belts around 1970.
2. Passive safety systems, from BMW's perspective, in the meantime have reached a high level of performance for passenger cars. However, the market is no longer only passenger cars and will continue to proliferate into different segments. This proliferation will require a need to transfer technology to these vehicles and, no doubt, dictate further innovative safety improvements.
3. Active safety systems will still have much more potential in the future for further reduced risk of accidents, especially when they will be able to actively communicate with intelligent road side or satellite infrastructure.

A little more detailed, I see the following development on vehicle safety:

First for **passive safety**:

**The future will show a refinement of body design, safety belt and airbag systems as follows:**

- We will have to put a higher emphasis on the partner protection issue (compatibility) by a corresponding design of the body in white, the bumpers and the engine packaging
- Safety belt systems will be self-adjusting to the particular occupants and accident severity needs
- Deployable safety systems (airbags) will be redesigned to automatically adjust their performance to the needs of the occupants and the severity of the accident
- We will move from simple control of safety systems to intelligent and even predicting, pre-crash sensors

Regarding the **post accident phase** we will have (and in some cars we already have):

- Automatic activation of post crash safety systems
- Automatic emergency call systems
- Automatic position detection and transfer to rescue
- Automatic data transfer of crash details to rescue

In the area of **active safety**:

There will be in a **first step** a continuous introduction of so called **onboard driver information and assistance systems** like e.g. GPS controlled navigation systems and automatic cruise control systems,

And in a **second step**

As a further improvement so called **interactive systems with road side and satellite intelligence systems** for the same purpose

We all do not know, and I personally doubt, if we will have totally auto-piloted driving in the foreseeable future.

For such a purpose, I would prefer to use, although admittedly not yet existing, a highly comfortable and easy accessible rail road transport.

This ends my perception of the situation and the future of road traffic safety.

## The Netherlands

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**Gerard J.M. Meekel**  
Ministry of Transport

During this session representatives of governments, manufacturers and manufacturer's organizations from United States, Japan and Europe gave their ideas and opinions on possibilities for improvements in road traffic safety. They referred mainly to:

- technical developments in the car (components, systems);
- changes and improvements in the infrastructure;
- and, last but not least, the influences of the human driver and his behaviour.

### TECHNICAL DEVELOPMENTS.

Concerning the technical developments in cars it became clear that such developments are still possible for existing safety items, e.g. improvements to nowadays common three-point safety belts, improvements to airbags with an even better timing of the deployment of airbags in accidents, improvements to the seat and seat positioning, decreasing the mass of a vehicle resulting in smaller forces in accidents.

Besides that, other components are already in existence or under development like airbags in sidewalls or under the steering column (lower leg injuries), all with the purpose to diminish injuries after an accident.

It became clear that such technical developments are performed very often by the manufacturers themselves without legal enforcement.

However, it is my strong opinion that legislative action by governments in introducing technical safety measures has quicker and greater positive effect on the introduction of life saving safety measures in cars than awaiting manufacturer's new developments. These are introduced in their products, on a voluntary basis, more as marketing instruments than safety devices.

Motorvehicle industry is globalizing to a greater extend. Such technical prescriptions for cars, their components and systems should therefore be globalized too and developed and applied on a global scale. To this and the Working Party 29 on the Construction of Vehicles (WP29) within the Economic Commission for

Europe (ECE), a subsidiary body within the United Nations is such platform for global harmonization of technical requirements.

Before developing and deciding on those global harmonized technical requirements it is necessary that basic research is done on a global basis too. To this end the IHRA (International Harmonised Research Activities) resulting from ESV-15 in Melbourne, Australia, can contribute in an extremely positive manner. This was understood as such too by the panellists.

Although manufacturers equip their motorvehicles very often with safety improving devices which are not required by legislations it cannot be understood that there is sometimes so much opposition when legislative technical prescriptions are developed which governments consider to have a great positive effect. Legislative enforcement of sound technical prescriptions should prevail voluntary manufacturers actions.

It is said too often that the manufacturers have to offer what clients expect.

Manufacturers offer also improvements which in my opinion are more marketing instruments than safety enhancing devices.

Also governmental proposals are sometimes opposed because it is said that they have as consequence an increase of the vehicles mass, which is in conflict with fuel consumption goals or environmental aims. However, very often manufacturers, on a voluntary basis, introduce all kind of non safety related comfort items which neutralize the positive effect of massreduction.

Manufacturers should have a more positive attitude to governmental safety enhancing items.

It is clear that because of globalization in the motorvehicle industry the technical requirements are to be harmonized on a global basis which, in the opinion of one of the panellists, will, because of that, result in an improvement of safety.

However, it should be taken into account that harmonization on a global basis can result in safety standards at the lowest common denominator and can

be a barrier to enhancement of motorvehicle safety.

Much attention is paid to protective aspects which are adapted to the individual driver and/or passengers (seating and mirror positions, adaptation of safety belts and airbags to individuals).

The question arises whether these developments are parallel to or instead of general safety aspects like for instance the protection of vulnerable road users (pedestrians or bicyclists) in contact with the front of private cars.

Also great benefit is to be expected with the introduction of front underrun protection for heavy goods vehicles, thus increasing safety on the basis of more general items than with individually adapted aspects.

We are not yet at the 80-20% rule: with the introduction of general and not too expensive safety devices a rather good enhancement of motorvehicle safety can still be attained.

## **CHANGES IN INFRASTRUCTURE.**

The relations between technical developments in cars and infrastructure can be seen in new systems.

Much attention was paid by the panellists to complete new systems e.g. smart vehicles equipped with various sensors and actuators.

Such vehicles diminish the necessary actions by the driver or correct the drivers activities when resulting in unwanted traffic situations.

Such influences on the vehicle's movements can be built-in in the vehicle or transmitted to the vehicle from exterior systems built in the infrastructure alongside the road.

This can be built also inside the pavement when considering AVG-(Automatic Vehicle Guidance) systems.

A lot of projects are under development or already realized on small scales.

It is without any doubt that such systems have their potentials.

However, the solution for the nowadays traffic safety problems will not be attained on a short term bases:

- no sufficient infrastructure will be available and suitable for e.g. A.V.G.
- No sufficient number of vehicles will be on the market in due time and at a reasonable price to fit in such systems.

Research and development on such revolutionary new systems should continue.

However, real practical application and introduction on a large scale as a replacement or even as an alternative to the existing systems is not to be expected within the next 20-25 years.

## **THE DRIVER AND HIS BEHAVIOR.**

Much is said by the panellists about the influence on road safety of the driver and his behaviour.

It cannot be denied that we are confronted too often with the negative aspects of excessive speed, alcohol and non-wearing of safety belts.

Legislation in general is sufficiently effective only on the condition that there is sufficient control and enforcement: no-control results in disobedience.

All panellists were strongly of the opinion that strong enforcement of traffic rules like listed above could remarkably contribute to an enhancement of road traffic safety, whilst technical improvements should continue to be developed.

A good driving behaviour should be preceded by a good education of the driver and could be maintained by a continuous information about and awareness of the consequences of non-obeying the relevant legal prescriptions.

How such improvements should be made is an item for another congress, not being an ESV-Conference (or maybe a next or the next ESV?).

## **MY CONCLUSIONS.**

New technical developments for basically new ideas should be based upon continuous IHRA activities.

Thus this can result in internationally, worldwide harmonized technical prescriptions, while safety standards at the lowest common denominator should strongly be avoided.

Safety improvements on a general basis should have priority above individually adapted safety systems and/or devices.

The "market" should be much less a leading factor in vehicle design or for safety aspects than the "government".

Governmental prescriptions should be more often the impetus to enhance the safety of vehicles: without binding governmental prescriptions the manufacturers do not contribute sufficiently; they relate their

developments for safety aspects much more to the "market".

A closer and more positive attitude between government and industry is needed in order to realize substantial effects on a short term basis.

Research and development for new technical systems like smart vehicles or automated guided vehicles should continue, but these will not be noticeably effective within the next 20-25 year.

Driver's behaviour and education is a very important aspect and should be improved intensively.

Control and enforcement in obeying traffic rules should be extended enormously.

Reduction of (fatal) injuries should be the paramount aim of all activities in this field, but one must be honest and realistic: traffic with zero fatalities will never occur.



# Invited Speakers Executive Panel

## Human Factors

Moderator: Y. Ian Noy, Transport Canada, Canada

### United States

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**R. Wade Allen**  
Systems Technology, Inc.

#### ABSTRACT

Driving safety can be realized through both crash worthiness and crash avoidance. Crash avoidance is to be preferred as it dispenses with damage, injuries and traffic delays. Crash avoidance can be realized through vehicle design and driver training. Simulation can play a key role in vehicle design and training, and is more likely to be applied as fidelity increases and cost decreases. Low cost simulations have a range of potential applications for the safety research, prototyping and training required to improve crash avoidance. The extent of the applications will depend on the realism, validity and cost of the simulations. Advancements in PC (personal computer) and associated technologies are dramatically reducing the cost of creating realistic virtual environments. Increased understanding of the computational requirements in simulating the vehicle operator's tasks allows enhancing the realism and validity of the sensory environment provided to the human operator. This paper discusses the general components and requirements for simulations, and the issues that influence the realism and validity of the sensory environment. Two examples are described of low cost PC based simulations. The first example is a truck simulator including full cab motion. The second example is a driving simulator that has been used in a range of research, development and driver evaluation applications.

#### INTRODUCTION

Simulation can provide a safe, convenient, and comprehensive environment for conducting research, development, training and certification of drivers. Traditionally the equipment and development costs have been quite high for simulations with adequate realism and capability. As the capability of PCs (personal computers) and associated technologies has increased, however, it has become possible to develop low cost simulations with relatively high end capabilities (e.g., Allen, Rosenthal, et al., 1998a). To achieve these capabilities, rich sensory information must be fed back at high update rates and with low

transport delay so that the human operator's sensory, psychomotor and cognitive tasks are equivalent to those when operating the real vehicle.

Visual, proprioceptive and auditory sensory feedback can easily be provided with recent advances in low cost, PC based technology. Motion cueing presents the most expensive component of low cost simulations, but new electro-mechanical devices allow a cost-effective solution to this difficult sensory display problem. In this paper we will discuss the application of real-time, human-in-the-loop simulations, and how low cost PC technology can achieve the required sensory feedback and computational capability required for relatively high end simulation applications in safety research, prototyping and training. In particular, such low cost simulation may be the only approach for widespread application of research and safety training of critical operations that represent a high accident risk.

#### BACKGROUND

Improvements in crash avoidance through vehicle design require methods for prototyping new equipment and exposing drivers to new designs. How can this prototyping and training be carried out under safety critical situations that represent hazard situations appropriate to real world driving? Consider the driver/vehicle/environment system illustrated in Figure 1. Each of the elements in Figure 1 can be simulated in some sense, and in fact, in order to evaluate new roadway designs the US Federal Highway Administration is developing an Interactive Highway Safety Design Model that simulates the driver, vehicle and environment (e.g., Allen, Rosenthal, et al., 1998b). For new vehicle designs however, the response of the driver is unknown, and so driver behavior is typically the focus of research studies in which simulation can still provide for the vehicle and environment.

When vehicle designs have proceeded to prototype hardware, instrumented vehicles can be run on test tracks or public highways to evaluate equipment and driver response. However, creating and/or controlling critical or hazardous road and/or



#### HIGHWAY ENVIRONMENT:

- Geometry
- Signs, Signals, Delineations
- Traffic

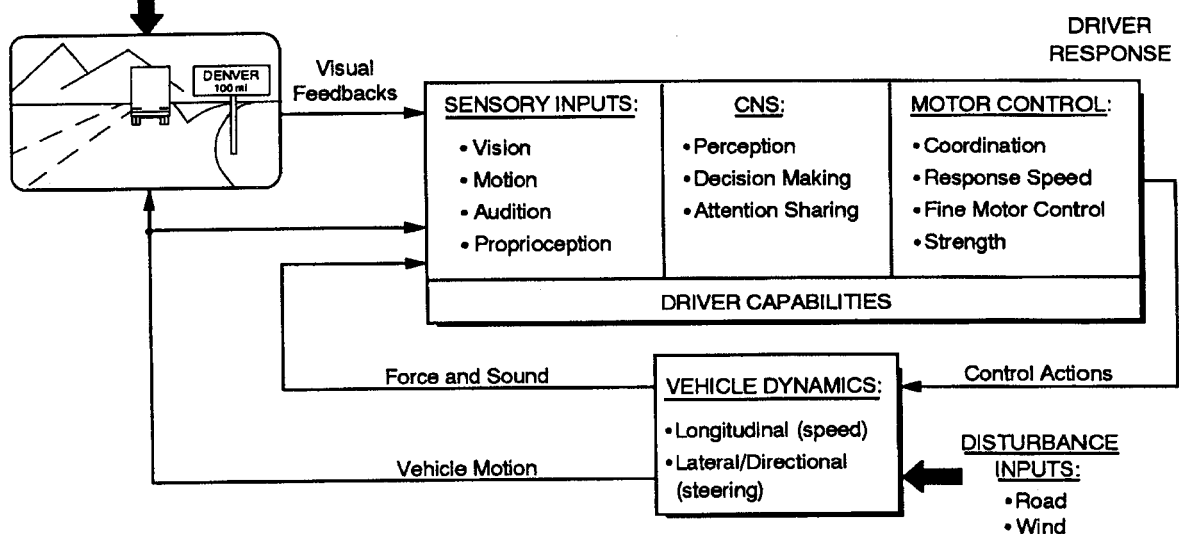


Figure 1. Driver/Vehicle/Environment

traffic situations is extremely difficult if not impossible on test tracks or in the real world (e.g., spinouts, rollover, brake fade on long, steep downgrades). Simulation can fill a critical gap for safety critical driving research and training.

The central thesis of this paper is that low cost PC and related technology can be used to reproduce realistic sensory feedback to the human operator in safety critical driving simulations. Processors, display accelerator chips and cards and operating system software advancements over the last few years permit the presentation of virtual environments that can quite adequately simulate the visual, auditory and proprioceptive cueing involved in vehicle operation tasks. Furthermore, the feedback can be provided with adequate update rates and minimal transport delays required for simulating the psychomotor and cognitive tasks typically involved in driving in complex environments.

Intel Pentium processors (i.e. 200 MHz MMX and faster) are now powerful enough to compute complex vehicle dynamics responses to the human operator's control input with adequate update rate to satisfy visual, proprioceptive and auditory cueing requirements (Allen, Rosenthal, et al., 1998a).

Windows NT software allows networking several processors for increasing computational capability. Networking can also be used to allow the interaction of several simulators. Low cost PC related display technologies, including head mounted VR devices allow visual and auditory information to be provided to the human operator. Low cost electro-mechanical torque motors and actuators can be employed to provide active control loading for effective proprioceptive feedback in vehicle control tasks. These low cost capabilities are adequate to meet the requirements of vehicle control simulation as discussed below.

Graphics accelerator and sound processor cards make visual and auditory cueing practical on PCs. These cards plug into the PC bus, and can carry out complex processing without loading down the host processor. The current flock of graphics accelerator processors and cards allows reasonably photorealistic scenes to be generated at 30 Hz. Based on simple commands from the host processor, current sound cards allow the reproduction of prerecorded sounds and the synthesis of complex sounds. Control loading can be provided with low cost electro-mechanical motors and actuators. There is also a new standard for

interactive game controls that give force feedback, and controllers in aircraft and driving configurations are currently available (e.g. Burdea, 1996). However, the response fidelity of this game controller standard is uncertain in terms of bandwidth and update rate as related to simulation requirements.

The basic processing requirements in a driving simulation can be described in terms of the diagram outlined in Figure 2. Here we show the human operator's closed loop control of vehicle motions

through visual, proprioceptive and auditory feedbacks. The visual modality is the most important since it allows the operator to compare the vehicle's path with a desired path in the environment and make appropriate corrections. Proprioceptive feedback can provide added information about the magnitude of control inputs. Auditory feedback can provide some additional information about the aggressiveness of vehicle maneuvering and possible situation awareness. The sensory feedbacks must reach the operator in a timely fashion, after allowing for delay by the

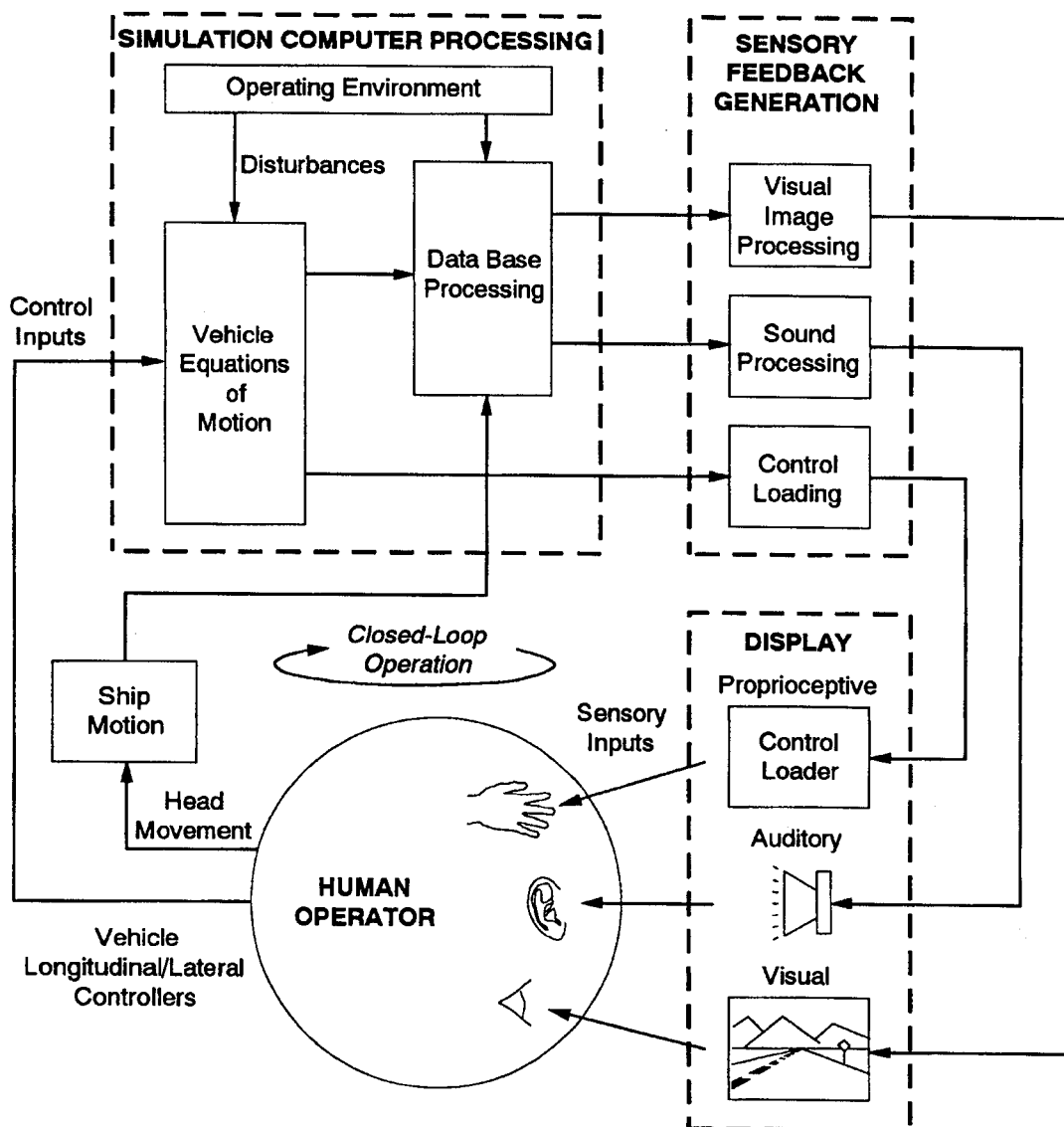


Figure 2. Basic Processing Requirements for Vehicle Operation Simulation

simulation computer processing and sensory feedback generation. Issues associated with the primary cueing modalities are as follows:

Proprioceptive (control loading) information must be returned to the human operator at the highest rate and lowest time delay of any sensory feedback in order to give realistic feel characteristics (e.g. Young, 1982). If proprioceptive cueing is dependent on simulation computer processing, update rates of hundreds of times a second with transport delays on the order of a few milliseconds are important here in order to give realistic feel.

Visual information must be returned to the human operator in less than 100 milliseconds with update motions on the order of 30 Hz or greater to give the appearance of smooth motion (e.g. movie frame rates are 24 Hz). Input sampling and processing can give delays on the order of 2 ½ frames, which result in transport delays of less than 100 milliseconds. Transport delay compensation can also be used to offset the effects of computation delay (Hogema, 1997). Resolution and quality of the visual display must be adequate for the required visual discrimination tasks. It is difficult to achieve resolutions below a few minutes of visual arc with low cost image generators and displays, so high acuity real-world tasks such as highway sign reading are difficult to simulate.

Motion feedback must correlate closely with visual simulation, so must be returned with a similar time delay (e.g., Allen, Hogue, et al, 1991 App. E). Practical, low cost platforms severely restrict motion, and so cueing algorithms have been developed to approximate the cues sensed by the human operator in the real world (e.g., Allen, Hogue, et al, 1991 App. F).

Auditory feedback has the least severe requirement for transport delay, with hundreds of milliseconds probably being acceptable. The frequency content or bandwidth of the auditory stimulus must match the human ear (on the order of 15 KHz), however, in order to produce sounds that are natural and recognizable. Doppler and stereo effects may be of importance in various driving scenarios.

Successful simulation development should include some validation procedures to verify the above response requirements and to ensure correct software implementation. Validation can include engineering methods applied to various simulator response characteristics (e.g., Allen, Mitchell, et al., 1991; Allen, Rosenthal, et al., 1992; Heydinger, Garrott, et al., 1990). The validation procedures should be designed to verify

software coding and the adequate responsiveness of the various cueing dimensions.

## EXAMPLE SIMULATIONS

Two examples will be given of driving simulations that each employ aspects of the low cost technology discussed above. The first application involves a truck simulation with full motion cab designed to provide low cost training and research capability. The second example involves a driving simulator that has found application in research and driver evaluation (Allen, Rosenthal, et al., 1998a). Both of these simulations have recently been upgraded with PC based photorealistic visual image generators that include graphics accelerators to provide high speed texturing, shading and lighting effects in the rendering process. The simulators have been designed for operational safety applications that cannot be accomplished in the real world with actual vehicles.

### TRUCK SIMULATOR

This simulator is suitable for both research and training, and includes comprehensive software and hardware modules for providing visual, auditory, motion and proprioceptive cueing to the driver. It is currently being developed by a consortium comprised of Mack Trucks, Moog, and Systems Technology, Inc., with software provided by Renault. Figure 3 shows the system architecture provided through a combination of hardware and software. The hardware consists of an instrumented truck cab mounted on a low cost Moog electro-mechanical motion base. Instrumentation

includes controls, displays, and torque feedback to the steering wheel. The visual surround is presented by a projection display system on screens at the front and rear of the cab. Stereo speakers and amplifiers provide auditory display. Intel Pentium processor based computers will handle all software operation. Cab I/O, visual image generation, sound generation, motion base and control loading commands are provided through auxiliary processor cards on the PC ISA and PCI buses.

The truck simulator software runs under Windows NT on several processors that communicate through an Ethernet link. Tests have shown the WinNTnet to be very fast (less than 2 msec delay) and very reliable (probability of a lost packet less than  $10^{-5}$ ). The software provides a variety of functions, including the vehicle dynamics, cueing commands for

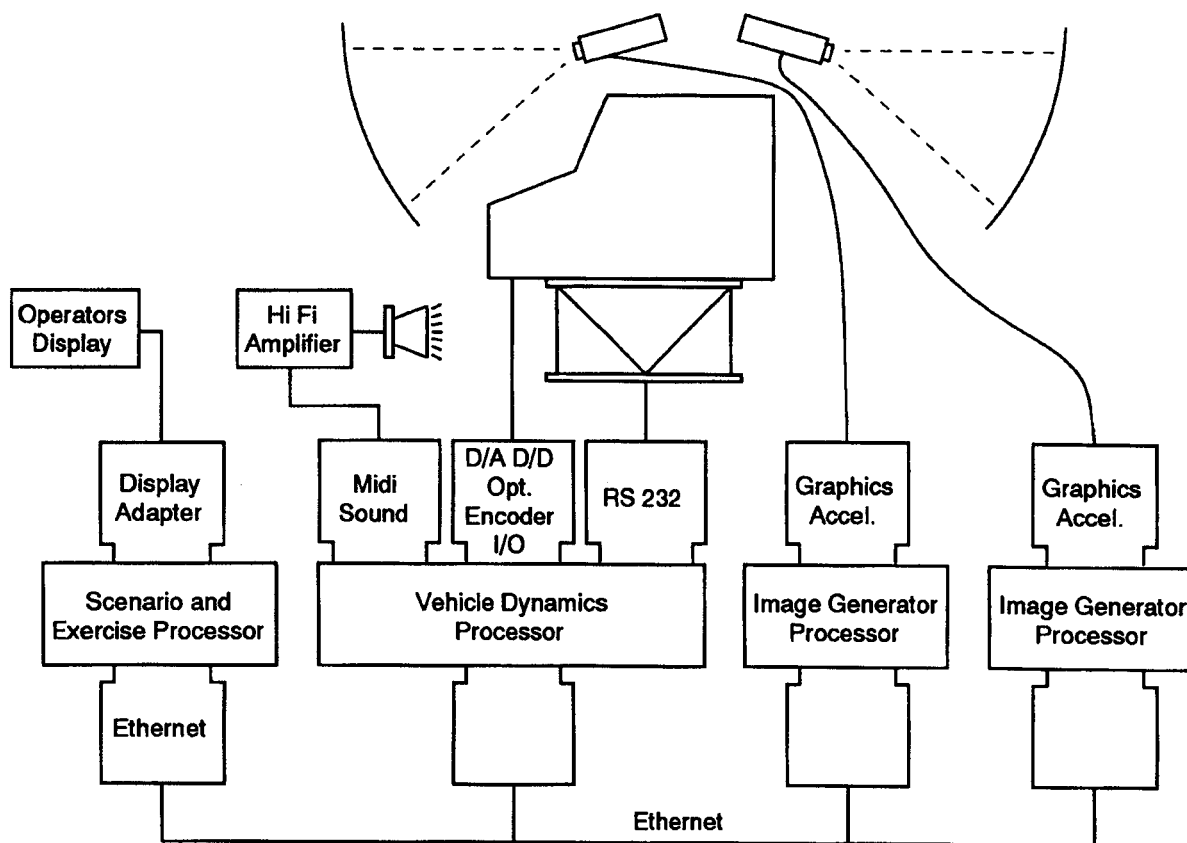


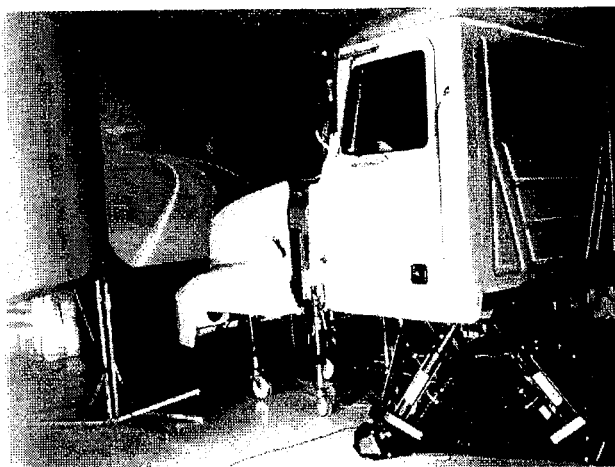
Figure 3. Truck Simulator Block Diagram

the visual, auditory, motion base and control loader systems, and other cab displays, and provides the visual data base and operator/instructor control functions. The software interfaces provide a significant opportunity for simulator variation required for research. The vehicle dynamics parameters can all be completely changed to simulate anything from light passenger vehicles to heavy busses and articulated trucks (Allen, Rosenthal, 1998a). The cueing command parameters can also be modified to achieve variations in the motion and control loading algorithms. The operator's control functions allow for changes in the visibility conditions, traffic conditions, placement on course, truckload, etc.

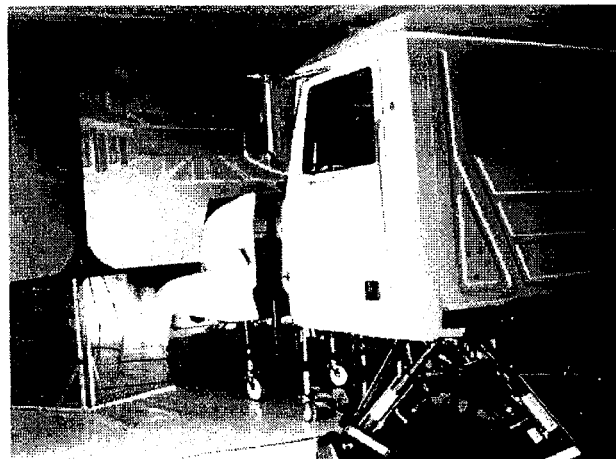
The IGs (image generators) consist of graphics accelerator cards running on a processor PCI bus. The cards are quite fast, and provide reasonably photo-realistic visual images at typically 30 Hz or greater update rate. The rendering speed is due to the 3Dfx

graphics processor chip that has found application in video games and real-time simulation (Real-Time Graphics Newsletter, 1997). The visual display projectors are high resolution, high intensity LCD units. The sound card is a high end Midi-compliant processor, and the sound electronics and speakers is high-end consumer level surround sound equipment. The host processors are Intel Pentium Pro 200 MHz. These can easily be upgraded for additional computational power.

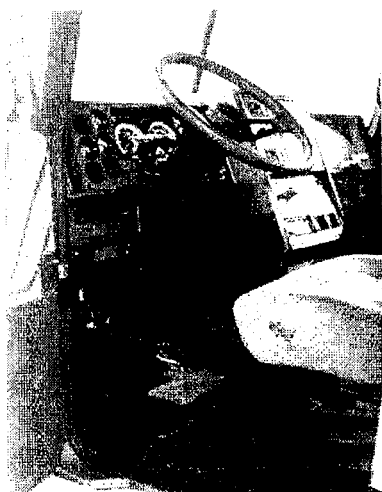
Some typical truck simulator pictures are shown in Figure 4. These photos portray the realistic appearance of the visual system and database, and the cab mounted on the platform. A real Truck cab (Mack CH) is provided along with actual controls and displays. The controls (throttle, brake and clutch) are instrumented with optical encoders that are interfaced with the vehicle dynamics module through an I/O card on the PC bus. The gearshift unit is instrumented with



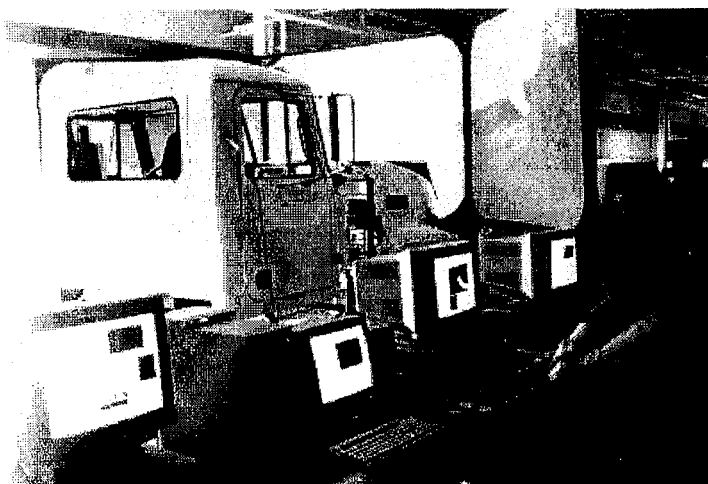
a) Cab + Motion Base on Upgrade



b) Cab + Motion Base in Town



c) Cab Controls and Instrument Panel



d) Operator's Station with Simulator PC Processors and Monitors

Figure 4. Truck Simulator Photographs

microswitches to indicate the gate and range level for gear selection. The microswitches are interfaced through a digital I/O card. The speedometer and tachometer are driven with frequency encoded signals from frequency converters commanded from D/A output channels.

Torque feedback is provided to the steering wheel by a torque motor commanded through a power amplifier from the VDM (vehicle dynamics module). Torque feel can be altered by changing parameters in the VDM associated with the steering system and power steering boost. The steer feel characteristics are

correct at zero speed (vehicle stopped), and change appropriately with speed depending on the simulated boost system. The steering feel command is generated in the vehicle dynamics at a 200 Hz update rate to ensure high fidelity steering feel.

The moving base platform is an electro mechanical hexapod configuration providing full six degrees of motion. The motion platform cueing is provided by the VDM at a 60 Hz update rate. The motion cueing is designed to provide transient acceleration and attitude rate cues, combined with tilt cues to simulate sustained maneuvering accelerations.

The VDM is realized in software, and provides for the dynamics of a complete tractor/trailer rig as discussed in Allen, Rosenthal, et al. (1998a). The VDM provides for the lateral/directional and longitudinal equations of motion, and safety critical truck characteristics such as brake fade due to brake

overheating on long down grades, rollover under hard cornering conditions, and jackknifing under appropriate steering and braking conditions. The VDM is computed at a frame update rate of 200 Hz, and provides cueing inputs to the IG, motion base, feel system and sound system.

### GENERAL PURPOSE DRIVING SIMULATOR

This application involves complex and validated equations of motion that allow vehicles to spinout and rollover under aggressive maneuvering conditions (e.g. Chrstos and Heydinger, 1997). The equations of motion also provide a steering alignment command to a torque motor connected to the steering wheel, which provides appropriate proprioceptive feedback consistent with steering input, vehicle maneuvering,

and road coefficient of friction. The operating environment includes road and aerodynamic disturbances, roadways of various alignments and interactive traffic. Sound processing with a 64 bit PC sound card can represent own vehicle sounds (engine, wind, tire screech) and sounds of interactive traffic.

Visual display can be provided by monitors, projectors, or a head mounted display. Wide-angle displays have been provide by three visual image generators with scenes projected on a 135 degree curved screen. A head-mounted display can be implemented in the same manner as described elsewhere for a parachute simulator (Hogue, Allen, et al., 1997). Typical roadway visual scenes are shown in Figure 5. Display requirements for tasks such as sign reading require resolutions on the order of 1 minute of arc. This is a difficult requirement to meet with a low cost image generator and display system. One partial solution to this requirement is to use separate high resolution but limited field of view sign generators with projected images that are optically combined with the overall roadway display (e.g., Hopkins, et al., 1997)

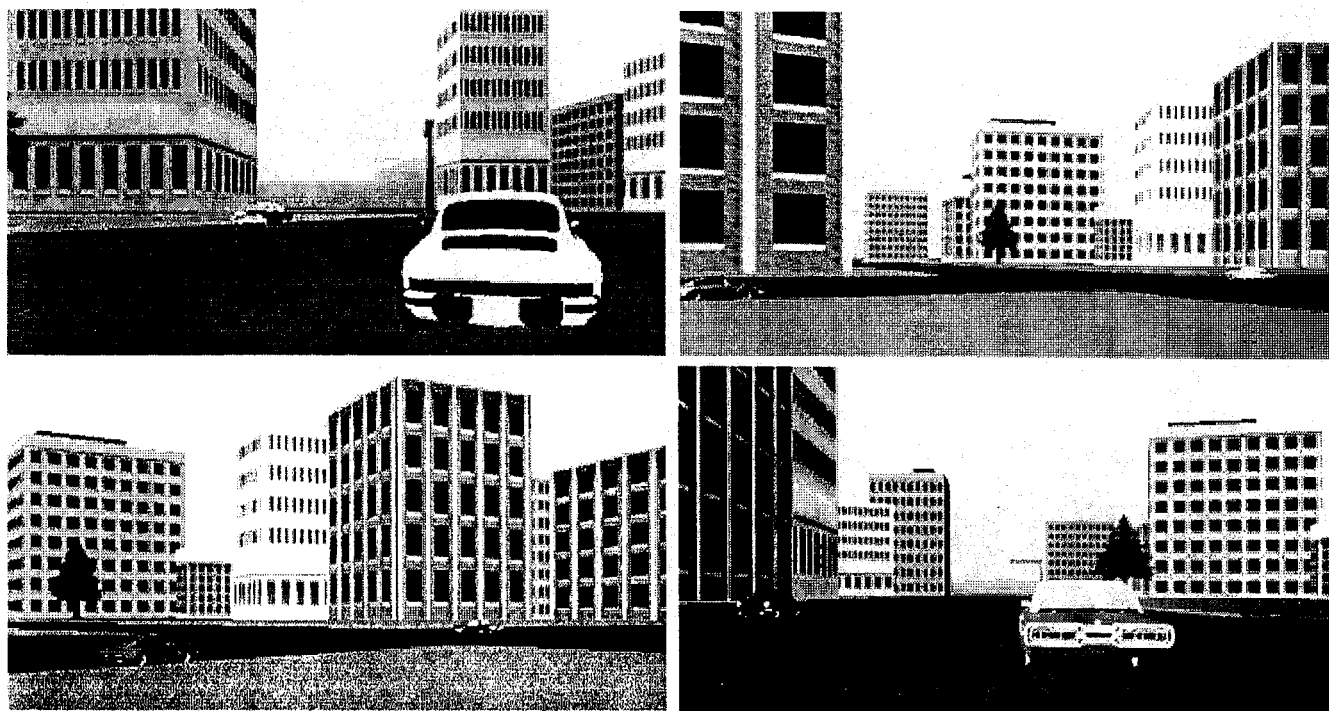


Figure 5. Typical Driving Simulator Roadway Visual Scenes

Multiple processors can be networked through the capability of Windows NT. Complex vehicle equations of motion can be run on a dedicated processor networked with the cueing command computer. Multiple visual image generators can also be run on separate processors and networked to a central cueing command processor to obtain multiple screens, wide angle and/or rear view displays. The use of a head mounted display requires only one image generator and gives a full hemisphere head field of view thus permitting drivers to look down side streets, or even over their shoulder to view rearward scenes. A variety of physical and display configurations for the driving simulator are shown in Figure 6.

The driving simulator has been used in a wide range of research and driver evaluation applications (Mollenhauer, et al., 1994; Musa, et al., 1996; Stein, et al., 1990). Simulator sickness with single screen displays (45 degrees FOV) has been less than 5%; with the wide-angle displays the sickness rate is on the order of 10-15%. Experience with the head-mounted display is just beginning, but experience with a parachute simulator application (Hogue, et al., 1997) suggests that the simulator sickness rate will be minimal.

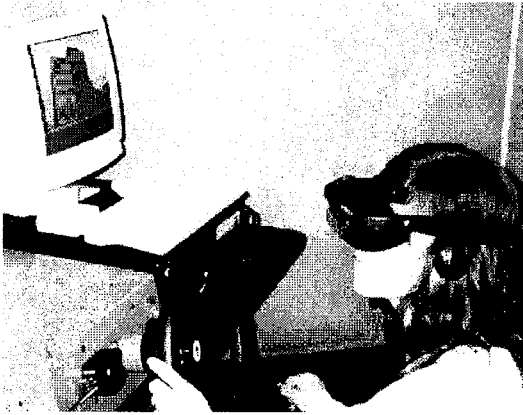
## DISCUSSION

The success of the above applications to date indicates that low cost PC and related technology can provide useful simulation capability. Given the current speed of Intel Pentium processors and the Windows NT operating system it is quite feasible to implement a complete VDM (vehicle dynamics model) as part of a

PC based driving simulator. The vehicle dynamics involved in the above driving simulator include lateral/directional and longitudinal dynamics, including driver train, steering and braking system characteristics. Even when a trailer is added to simulate a tractor/trailer rig, the VDM can still run at 200 Hz well within real time. This means that even in the most demanding of simulation conditions, a Pentium based processor can adequately handle situations such as hardware-in-the-loop applications, and high fidelity steering feel. Running similarly complicated flight dynamics should not be a problem.

Pentium processor based PCs can also adequately handle the generation of other cueing dimensions, including visual displays and sound. Graphics accelerators are available that will provide photorealistic rendering of visual scenes including texturing, lighting effects and shading. Sound processing cards can provide and mix a range of recorded and synthesized sounds, and can also include stereo and Doppler effects. Thus PCs seem poised to provide low cost driving simulation for a wide range of applications in safety research, prototyping and training.

These applications will benefit from current and ongoing developments in the PC industry as processor and graphics accelerator capabilities become faster and more powerful. Cueing devices such as visual displays and sound systems are also becoming more capable. There is also significant development occurring in electromechanical motion systems and electronic instrument panels which will improve performance and lower cost to the level that can be considered in low cost, PC based simulations.



*a) HMD and Game Controls*



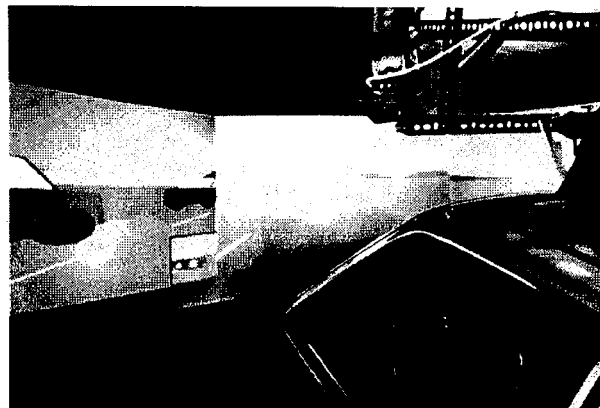
*b) Torque Feel + Monitor*



*c) Free Standing Console*



*d) Game Console*



*e) Cab with Projection*

Figure 6. Various Physical and Display Configuration for a Driving Simulator



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## INTRODUCTION

Under the heading Intelligent Transportation Systems (ITS) many different types of driver support systems have been or are being developed. Generally speaking, these systems can perform any one function or combination of functions of the following options:

- provide information or warning; this can be:
  - \* information that is relevant for the driving task like traffic information, traffic management instructions, route guidance and warnings like collision warning or exceeding of the local speed limit etc.
  - \* information irrelevant to the driving task like business information etc.
- monitoring of vehicle- and driver status
- support certain parts of the driving task: this concerns concepts like ABS or traction control, the Intelligent Speed Adapter etc.
- substitute certain parts of the driving task: this concerns concepts like Adaptive Cruise Control (ACC), collision avoidance, lane keeping etc.

Apart from information that is not related to the driving task, all systems are aimed at supporting the driver by providing new functions, simplifying control operations, compensating for weaknesses in driver behaviour or impeding undesired behaviour. Theoretically, such enhancements of the vehicle's functions should make driving easier and often safer, but experience with sophisticated automation in other modes of transportation e.g. the aviation industry, alerts us to the possibility of unwanted side effects. Apart from purely technical problems, most of these side effects are caused by inadequate interaction of human controller and automated system. In order to understand why these effects occur and to prevent them in the future we need a frame of reference that provides insight into the strengths and weaknesses of human control behaviour, in this case while performing the driving task.

At this moment, a really comprehensive behavioural model of the driving task does not exist. However, a number of existing theoretical considerations can be put together to form at least a partial framework that can be used to examine possible effects of ITS. There are examples of fruitful application such a synthesis in the

field of aviation where the problems concerning electronic support of the human control tasks have led to the development of Situation Awareness (SA) theories, first developed by M.R.Endsley. [Endsley 1988]

## ASPECTS OF THE DRIVING TASK

### Theoretical Reference Model

This Situation Awareness framework, developed originally for application to aeronautical situations, also seems suitable for application to the driving tasks since it incorporates many of the theories that have been applied to the driving task in the past.

Moreover, important existing concepts in safety regarding the influence of task load can well be accommodated in the SA framework. Therefore, the SA framework shall be used here as a general reference. In this concept, SA is distinguished on 3 levels:

1. perception of elements in the current situation
2. comprehension of current situation
3. projection or prediction of future status.

On the basis of SA on these levels decisions are taken and control actions performed.

At this point, it is important to realise that in contrast to civil aviation, where the interaction of the pilot with the aeroplane dominates the pilots tasks, the driver of a motor vehicle spends relatively little time operating the vehicle and much more time interacting with other road users. Therefore, Situation Awareness in a driver is for an important part defined as observing, understanding and predicting the behaviour of other road users. So far practically all developments in driver support systems have primarily been aimed at support of vehicle control tasks, route finding, general traffic status information etc. and not at the support of these interaction aspects. Still, since support systems can modify individual behaviour, interaction aspects must also be considered when pondering possible effects of ITS. Therefore this contribution has two parts:

- considerations regarding effects on the individual driving task (chapter 3)
- considerations of effects on traffic interaction (chapter 4).

## Important Elements of the Individual Driving Task

In order to explain some of the human possibilities and limitations in a control task, we have to look more closely into the mechanisms of how the SA levels can be achieved. In the course of the last decennia, several theories have been put forward that are helpful in this respect. For instance, the multiple resource theory [Wickens] that implies that the human operator possesses a limited capacity to execute certain tasks simultaneously, seems relevant. Tasks will be executed easier (with lower task load) if certain simultaneous tasks demand separate resources. Conversely, if certain tasks compete for the same resource, problems of prioritising and sequencing tend to overload the resource.

Furthermore, cognitive information processing in human beings and subsequent action is relatively slow, a/o because of a natural minimum timelag (the neuro-muscular gap) of 120- 200 ms of processes without cognitive interference. Cognitive processing takes a variable amount of time, thereby also increasing the timelag between input (perception) and output (control action). Although the versatility of the information processing allows the operator to adapt to various process dynamics, this timelag still limits the control of swiftly changing processes. This has already been described in the 1960's by the Cross-over model [McRuer 1969], which, however, applies primarily to control behaviour in a single task. In more complex tasks, that involve more parameters and several sources of information, another limitation of the human controller becomes manifest: while multiple information can be gathered more or less simultaneously in a so-called pre-attentive state, attentive perception of multiple information sources is difficult.

Driving in traffic in general and especially in a urban surroundings, can be characterised as a process with sometimes rapid changes, a varying number of sub-tasks and multiple sources of information that are spatially distributed.

The human controller has developed a number of strategies that compensate the limitations and make effective control possible. These strategies, which are highly relevant for the interaction with support systems, can be summarised as follows:

1. *prediction*: instead of reacting to traffic phenomena after they happen, the driver tries to make short term predictions and acts on the basis of the prediction rather than on the actual situation: in this way the delay time can be compensated. This prediction requires some sort of internal model of the responses of the own vehicle and the traffic behaviour of others, given the

context of the traffic situation, the traffic rules and other external conditions.

2. *piecewise modelling*: in order to make the control process fast enough its processing time must be limited. Therefore the operator seems to employ a repertoire of partial models for different traffic situations rather than a single, comprehensive, model. These models are referred to as *schemata* in the SA model. They contain a limited set of key features that are used to structure the perceived data rapidly into comprehension of the situation and also provide the basis for prediction. The schemata speed up the cognitive process, which is necessary in a highly dynamic environment, but also limit the number of perceptual parameters and relations that are processed or can be predicted.

3. *scanning and sampling*: limitations of resources and considerations of relevance of the data source cause the human operator to switch attention sequentially to those sources: the data-acquisition tasks are "chopped up" in pieces that can be processed. The attention is temporarily focused on an information input source (visual or other) which is briefly examined (sampled). Depending on the nature of the observation, the data can be used immediately or the information can be committed to memory for later evaluation. Thus, the time used to complete a scanning cycle can vary considerably and if this time tends to be too long, certain elements can be temporarily left out of the scanning sequence. This provides a means to speed up essential processing and reduce the overall task load, albeit at the cost of missing certain information

4. *simple dynamic limitation criteria*: those sources of information that can be associated with some kind of limit value (e.g. the distance to an obstacle, traffic lane boundary, etc.) will probably have a dynamic criterion for action [van der Horst],[van Westrenen]. This implies that not solely the distance to the limit is used to trigger an action but the *estimated time until the boundary will be reached*. Of course, also excess of the limit will be cause for action (but in that case it often too late!). So far, this type of dynamic limitation criteria has only been postulated for visual characteristics. In any case, this finding has implications for supportive feedback of safety criteria that current ITS concepts do not account for.

5. *automation of frequently performed task sequences*: human controllers are able to automate certain complex motoric sequences (e.g. all the actions involved in changing gears) so that a sequence can be started if necessary and run its course without requiring conscious attention. Such sequences are often called *scripts* or *skills*. Once these sequences are started they are hard to interrupt. These scripts execute quickly, are less error prone than conscious behaviour and require

much less energy. If an interruption of a script does occur somehow, remedial action usually takes a relatively long time because a cognitive analysis must be made of the interrupted state.

6. *adaptation or learning*: learning is the mechanism that has enabled the human operator to develop the previously mentioned compensatory strategies in the first place. Learning is also highly relevant to the introduction of ITS support systems: it is almost a certainty that a driver will learn to incorporate these systems in the driving strategies but how, when and to what end is less obvious and almost certainly not only dependent upon the *intended* functions of the ITS. Therefore available knowledge of mechanisms that govern learning is indispensable to an assessment of possible effects of ITS. Up to now, this has been poorly researched.

This consideration so far contains mostly task elements on the tactical and operational level and does not contain some important aspects of behaviour like the influence of motivation: attitudes and convictions and moods, the influence of drugs etc. Also the strategic level (choice of mode of transportation, time of trip, general route planning etc.) has not been addressed. These aspects are undoubtedly relevant but will not be addressed here.

## **SUPPORT SYSTEMS AND THEIR POSSIBLE EFFECTS ON THE INDIVIDUAL DRIVING TASK**

We will distinguish safety effects on several levels of the traffic system:

- A. Intended effects
- B. immediate effects on individual behaviour with:
  - 1. effects on taskload
  - 2. controller-out-of-the-loop problems
  - 3. effects of the Human Machine Interface
  - 4. effects of multiple ITS devices
- C. Indirect effects on traffic behaviour
- D. Long term behavioural adaptation.

We will now examine these effects separately.

### **Intended Effects**

It is of course very important to see whether the intended effects of the various devices are indeed manifest. These intended effects need not always be aimed directly at increased safety however; often devices are meant to alleviate tedious parts of the driving task (e.g. cruise control), to facilitate otherwise cumbersome functions like route finding or to provide otherwise unattainable information (the presence of

congestion further on). Increased safety is then claimed as a side effect.

First, let us consider information systems. There are not many devices that really have proven themselves in practice: only traffic management systems and Radio Traffic information of various implementation have been used on a large scale. These systems have so far proved moderately effective in achieving a higher level of safety and improving traffic flow. [De Kroes 1983],[Verwey 1996]. Other systems, like route guidance, exist on a much smaller scale and so far have not shown particular safety effects. Devices providing information *not* related to the driving task like car telephones have evoked serious doubts about their safety [Maclure 1997], [Brookhuis 1991]

Experience with other support systems derives largely from laboratory- and simulator tests and from small scale field studies (often in a well controlled environment). Many studies indicate that positive intended effects on driving behaviour are indeed detectable but rarely in a very convincing way because these effects are offset by simultaneous adverse effects. However, some devices that are currently studied seem to have a potentially large positive effect on safety. One such device is the Intelligent Speed Adapter (ISA) [Almqvist 1991],[Godthelp 1991], [Persson 1993], a device that somehow interacts with the driver to decrease the speed only when the local speed limit is exceeded. Although experiments are still under way, expectations are that the positive effects far outweigh the negative.

Generally speaking, from a theoretical standpoint, it must be possible to enhance the quality of Situation Awareness of the individual driver and simplify the driving task in complex situations without distraction and to simplify vehicle operation without out-of-the-loop effects. Learning how to emphasise these positive effects and suppress the negative ones is still a considerable challenge to researchers.

### **Immediate Effects on Individual Behaviour**

**Effects on Task Load - Underload** - Underload is defined as the situation gets into a state of limited attention to driving (no specific driving task demands) or deactivation (dozes off).

Underload can be brought about primarily by devices that partly take over the driving task like Cruise Control, which leads to a state of lessened vigilance (see a/o Riemersma, Rumar, Wickens, Wiener and Yaouta) if combined with traffic conditions that are not demanding. This may occur in longer trips on a quiet motorway (Highway Hypnosis [Wertheim 1978]) or an

other road with monotonous characteristics and especially at night.

In an urban setting, the (remaining) traffic tasks are usually such that underload can be considered no real danger. Only e.g. while tiredly driving by night in a deserted street could ITS induced underload conceivably lead to increased risk. This condition must be considered rare.

#### *Overload - Information presentation by ITS*

As indicated before, task overload is thought likely when several cognitive tasks compete for a single resource. If the tasks indeed need to be executed at practically the same time a stalemate will follow: the resource can process only one task at a time and this results in at least one task being ignored. (It should be noted that automated tasks (scripts) usually do not compete). The subject of task load associated with information presentation has been examined quite extensively a/o by Antin, Kaptein, Parkes, Steyvers, de Waard, Verwey, Wierwille, Wickens, and Zaidel.

In general, the normal array of traffic tasks are not so critical and mostly tolerate some postponement. Still, competing tasks require extra decisions concerning their priority which increases the effort required. Since it is often estimated that 90% of all information input goes by way of the visual channel the channel is considered a prime candidate to produce overload. The addition of yet another visual task by ITS applications therefore is considered undesirable. This is especially relevant in an urban setting where a large number of relevant information sources is present that all have to be scanned: a constantly changing layout of the infrastructure, a large variety of traffic signs, different types of road users from a variety of directions and generally high differences in speed (higher than on a motorway) between them all make for a highly loaded visual resource. Moreover, different traffic rules apply to different types of road user and different types of infrastructure which also makes it more difficult to choose an appropriate schema and select appropriate actions, so the "decision making" resource is also more highly loaded than on a motorway.

As remarked before, if task load increases some items are often left out of the scanning sequence. Research [Verwey 1991-1993] has shown that some ITS applications with a visual interface that do not convey high-priority information are often neglected when the traffic situation outside is demanding. This suggests that drivers are effectively prioritising their visual input. The device is only observed again when the situation allows that and the possible negative influence on safety is then small. The latter of course, only if the driver really can ignore the device: some cues, like flashing lights, prove very difficult to ignore!

We must also realise that this adaptation of the scanning cycle is only possible if the driver can access the information source whenever he/she wants it, or in other words if the task is *self-paced*. However, if the information source is located outside the vehicle, on the roadside, the driver can only access the information in a limited area (and time) before the sign is past and this is called a *force-paced* task. Other examples of forced-pace tasks are auditory displays that only produce their information at a certain moment and cannot repeat that same information whenever the driver wants it.

Generally speaking, all devices that employ force-paced tasks limit the possibilities of the driver to regulate the task load. These devices produce a higher risk of overload, especially in urban traffic! But even if the devices are self-paced, some detrimental effects of visual displays remain detectable in the driving behaviour, like larger lateral displacement and later braking before crossings. Self-paced auditory displays show less of these effects.

Note 1: Even without inducing overload, ITS information systems can still increase the driving risk somewhat. This is due to the extension of the normal scanning cycle by the display: it can occur that, while attention is temporarily fixed on the display, an important event elsewhere is not observed. While there is no elevated taskload in this case there is still the danger of an accident due to this oversight.

Note 2: For some types of devices, urban traffic provides an escape from these difficulties: the frequent stops at traffic lights could be employed to convey certain information without endangering traffic behaviour.

#### *ITS devices that take over part of the driving task*

Many of the devices that are intended to take over part of the driving task like ACC, lateral driving support etc. are mostly intended for operation under motorway conditions. As such they have been designed to alleviate the driving task. In urban circumstances, where frequent changes of course and speed are normal, these devices should not operate, yet if they still do may cause serious complications. The driving behaviour they (more or less) enforce is often contrary to usual driving behaviour in urban traffic as expected by both the driver and surrounding road users. Constant speeds, large time-headways or a straight course are unusual in urban traffic and if the support systems are not switched off they may give rise to the driver "fighting" the automated system while neglecting the surroundings. There have been examples of such "fights" in recent incidents in highly automated civil aircraft. [Stanton & Marsden 1996]

## Human-Out-of-the-Loop Problems

A specific problem with support devices that take over parts of the tasks of a human operator is associated with loss of vigilance and eventually loss of certain skills [a/o Endsley 1995].

The operator's role is reduced to supervision of the system, but the supervisory activities are often neglected or omitted entirely, thus freeing capacity for other activities

As an example of short term effects of this nature: research using driving simulators [a/o Stanton, Young & McCaulder 1997] indicates that drivers will readily adapt to anti-collision devices and will completely rely on the device after only a short adaptation period of time. If the simulated device is made to fail (e.g. it does not "see" an other vehicle) more than half of the drivers tested fail to take effective action and crash!

Again, these tests have been made under motorway conditions. In urban conditions, with a multitude of moving and stationary obstacles, failure of the automatic device is far more probable than under the relatively simple motorway conditions. This sort of adaptation could therefore prove far more dangerous in an urban setting.

Research indicates that human controllers who have developed certain skills and are then placed in a supervisory role will perform better in the previously mentioned situation than human controllers that have never developed the specific skill because they learned to work with the support system from the start. This indicates the possibility of a long term deterioration of road safety: if future generations are trained solely in vehicles with all possible support systems they will not develop the skills associated with "manual control" that are required without support or with failing support.

There is also another, long term risk involved in progressively automating human tasks, specifically when the automaton becomes more and more complex. In this case the human supervisor may construct an internal model based on partial or even mistaken understanding of the system. This can lead to either misplaced trust in the systems safety in certain conditions or to unnecessary interventions by the supervisor.

## Effects of the Human Machine Interface

Many of the effects mentioned in the previous paragraphs are related to the design of the Human Machine Interface (HMI). Research in the past ten years into the HMI has provided much insight into many practical parameters that interfaces have to comply

with. The results cover such items as placement of displays, contrast of the display and ambient light, use of standardised symbols and other ergonomic characteristics. Also safe limits of necessary sampling time (ca 1 s) and maximum number of samples (3) have been established for visual displays. Rather than going into all the details, it suffices here to refer to specific research [a/o Heijer 1998], some national guidelines and the new (concept of the) European Code of Practice for such an HMI. It should be emphasised however that knowledge on the subject of an optimal HMI for all sorts of functions is still far from complete.

One of the problems that still remain is, that most of the research has been carried out using a single ITS device. Guidelines usually state that criteria for single systems should also apply to multiple systems as a whole, which implies the need for a standard for integration. As things stand now, this standard is still lacking (and not to be expected soon!).

## Effects of Multiple ITS

So, one of the problems with primarily commercial development of ITS devices is, that co-ordinated development does not necessarily exist. If drivers can equip their vehicles with an arbitrary selection of ITS applications, a number of different problems can arise as a result of lack of co-ordination. These problems include:

- the placement of multiple displays, making the scanning task unacceptably more complex
- simultaneous messages, with all possible mixtures of modes (visual, auditory, tactile) that arrest attention and demand time to sort out
- conflicting instructions or even actions by autonomous devices

Again, especially in an urban environment, the resulting confusion and interference with the already complex driving task must be considered highly undesirable.

## Counterproductive Behavioural Adaptation

Counterproductive behavioural adaptation is the phenomenon that drivers start behaving in riskier ways as a result of a perceived increase in safety provided by an ITS device (or any other device). This is an effect on the individual level rather than an effect on traffic interactions.

These longer term effects still have not been very well researched and are often speculative. However, there are indications that these effects must be taken seriously.

As an example, drivers of vehicles equipped with Anti Blocking Systems have shown some adaptation to the device a/o. by increased speed under adverse conditions. Introduction of ABS seems to have changed the types of accident these drivers get involved in rather than having decreased the number of accidents.

Also, experiments with an intelligent speed limiter, in this case only an advisory system, evoked adaptation. The system showed the current driving speed in relation to the local speed limit in three stages: lower than the limit, 0-10% excess and more than 10% excess of the limit. Practically all drivers adapted their speed to the range 0-10% excess, effectively homogenising their speed but also increasing their average speed, in almost all environments, including the urban. [Brookhuis]

Similar effects of automatic devices have been observed in aviation and the process industry where high levels of automation have often introduced new types of accidents due to unintended or unforeseen adaptations in human behaviour. Also, limited understanding of the complex automated processes by the operator has proven to be a source of severe errors. [Satnton & Marsden, 1996]

### **Indirect Effects on Traffic Behaviour**

Indirect effects can be defined as behavioural adaptations on levels or modes of behaviour that are not directly related to the function(s) of ITS devices. Following a traditional model we can distinguish different indirect influences on the safety of traffic flow and on the strategic level and the tactical level of the driving task.

**Influence on the Safety of Traffic Flow** - Over the past decades, motor vehicles have progressed to a state where differences in handling, road holding and technical reliability between different brands have become practically irrelevant. This homogeneity allows a simplification of driver skills and also makes prediction by judging a vehicles movements more reliable. In this way, car manufacturers have effectively contributed to a marked increase in overall road safety.

The introduction of a large variety of support systems, applied in a rather random fashion may once again introduce dissimilarities between vehicles which will probably result in a deterioration of overall safety.

**Influence on the Strategic Level of the Driving Task** - On this level indirect effect have to do with undesired use of motorvehicles indirectly due to ITS. One expected general effect of automating difficult or dull parts of the driving task is that driving becomes more attractive which will lead to an undesired increase in the use of motorvehicles. Another effect of ITS, or

more specifically route and traffic information systems, may be a redistribution of traffic through areas where high traffic densities are not desired.

Furthermore ITS systems that improve the handling characteristics of vehicles may lead to increased use of those vehicles under adverse weather conditions like heavy rain, snow or icing.

**Influence on the Tactical Level** - On this level indirect influence of ITS can manifest itself as creating time or opportunity for undesired activities that are not related to the driving task. These tasks can than distract the driver to such an extent that the activity consumes more than the available extra time.

Car telephones can be considered an example of such devices: they introduce a mental task (maintaining the conversation) that is totally unrelated to driving and thereby can introduce interference with the mental processes that are vital to driving. Again this can be especially dangerous in urban areas where the traffic task is demanding.

Another example are TV devices in the car that may distract the driver from the traffic task.

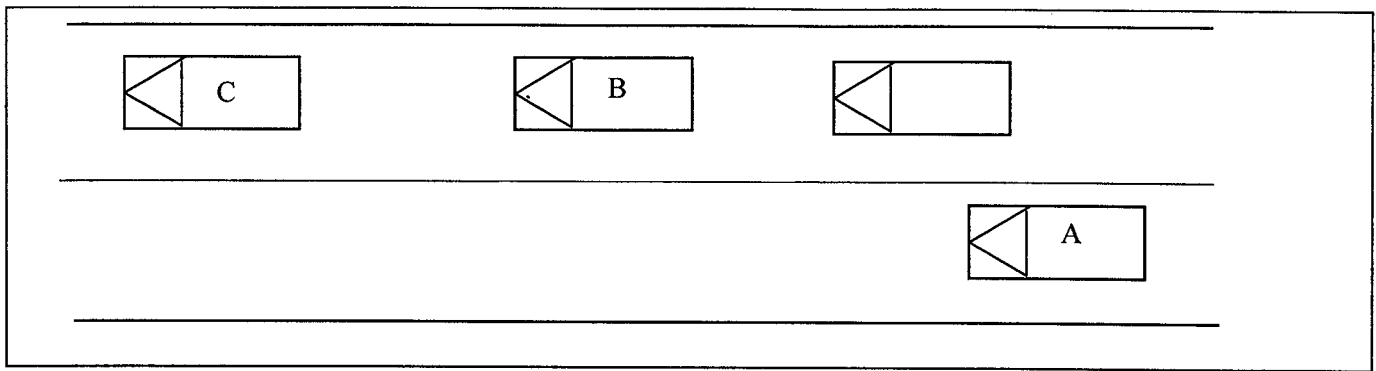
Also devices intended for support of the driving task like anti-collision devices may lead to such problems: by creating "free time" for certain tasks the driver may be tempted e.g. to be more deeply engaged in distractions like (telephone) conversations or listening to the radio.

### **Effects on Traffic Interaction**

As stated before, the average driver spends relatively little time operating the vehicle and much more time interacting with other road users. Predicting possible behaviour of those other road users therefore features strongly in the predictive strategies described in chapter 2. Since the interactions are virtually anonymous the predictions must be made on rather superficial behavioural cues of the road user's movements and these movements can only be observed for a limited time. This means that the basis for prediction (presumed present in the schemata) must be a generalised model, an average.

If an ITS support systems somehow changes one driver's behaviour in such a way that behavioural cues do not correspond to average intended behaviour, this change will disturb the prediction of another driver and so may render the situation less safe, even if this modified behaviour is safer from a individual point of view. This is best illustrated by an example:

Figure 1 depicts a motorway situation where vehicle A overtakes a row of other vehicles. The driver of A must try to predict whether any of the other vehicles



**Figure 1.**

will also start an overtaking manoeuvre. In this example, vehicle B is in fact preparing to overtake C. Normally, this intention is communicated by a narrowing of the gap between B and C (the flashing direction indicator is usually only used at the last moment and has no predictive value!). Now, if B should be equipped by ACC, the vehicle will probably not display this cue, since the automatic system maintains a constant headway. Of course, the driver of B may override the ACC system and still display the usual behaviour, but it is far easier to let the system take care of headway maintenance and prepare for the overtaking manoeuvre leisurely.

In this example, the driving situation is actually made safer for driver B, since the risk of colliding with C during the preparation (looking in the mirrors etc.) is effectively eliminated and the driver's taskload is also somewhat lower. For driver A however, the usual cue is absent (on the contrary: the behaviour seems to confirm lanekeeping) and the driver may be startled into an emergency reaction by unexpected overtaking of B with the associated unsafe consequences.

This sort of problem will particularly be evident during the time that only few road users are equipped with advanced support systems. The other drivers will not encounter modified behaviour often enough to adapt their strategies. Eventually, if many or most vehicles use these systems, behavioural adaptation will probably lead to the use of other cues and thereby reduce the risk again (as drivers generally seem to have done in the past 20 years).

## DISCUSSION AND CONCLUSION

In the previous considerations we have tried to describe possible effects of ITS on road safety by considering possible effects mostly on tactical and operational levels of driver behaviour. We must realise, however, that although these behavioural effects may be valid, this is not completely equivalent to estimating the effects on the actual occurrence and severity of road

accidents. Not every driver error will be "translated" into an accident, on the contrary: the traffic system seems quite tolerant for errors. For an important part, this may be caused by the same driver characteristics that have been reviewed: the predictive and adaptive strategies that drivers employ will also allow them to compensate failing behaviour of other drivers to a certain extent. This makes more detailed understanding of the how's and why's of these strategies all the more important, which implies that we must search for methods to measure important parameters of the internal processes more directly.

So far we can conduct a large variety of experiments and measure many details of driver externally observable behaviour but exactly how to translate these measurements into effects on actual accidents still eludes us. In fact, along with the use of these "objective parameters" the use of expert opinion, like the opinion of experienced driving instructors, is often considered indispensable to judge behavioural effects in experiments. For this reason, we cannot say that we can fully interpret or predict behavioural effects of support systems.

Maybe this is one of the reasons that the development of all sorts of automated systems to support or expand the possibilities of the driver so far has been dominated by technical and economical considerations which has produced systems that are primarily oriented on operational tasks of the driver. A major part of the driving task and a part that is highly relevant for safety: interaction with other road users, has received much less attention. More thorough and coherent research into this area, for instance along the lines that have developed in other modes of transportation like aviation, is necessary to avoid many of the side effects mentioned and to optimise support.



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### ABSTRACT

As intelligent transportation systems (ITS) become more available, drivers must cope with increasing amounts of in-vehicle information. While the intent of providing such information is to make driving safer and more convenient, the aggregate of all this new information may paradoxically decrease vehicle safety if good human factors principles are not used to implement ITS. This paper first discusses the need for ITS integration by reviewing two major new sources of in-vehicle information: collision avoidance systems (CAS) and advanced traveler information systems (ATIS). System integration is then defined in terms of system characteristics and their effects on the driver. ATIS guidelines illustrate first-level system integration. This paper concludes with a discussion of the safety implications of ITS.

### INTRODUCTION

Modern technology has enabled the development of sophisticated computer-based user support systems in a variety of industries. Such systems are available today in such diverse areas as nuclear power control rooms, commercial aviation cockpits, air traffic control centers, and surface, air, and subsurface military weapon systems. The primary aim of all these systems is to assist the users in performing their jobs more safely and efficiently. Such is also the case with the burgeoning information systems being incorporated into passenger and commercial vehicles as a result of the effort through the internationally recognized program entitled, ITS to field sophisticated electronic systems to improve highway transportation.

In-vehicle information systems (IVIS) can be categorized by functional areas such as: collision avoidance, traveler information, and driver convenience. The collision avoidance technologies will address areas such as road departure, lane change and merging, rear end collision avoidance railroad crossing warning as well as advanced cruise control

and drowsy driver warnings. The ATIS, which will be offered as part of the vehicles of the future, include information in such areas as routing, navigation, safety and hazard road advisories and warnings, traffic and congestion, motorists services (i.e., yellow pages information), vehicle status, weather information, and supplemental highway sign information. Commercial and transit vehicles will also include applications designed to support those vehicle's operational objectives such as cargo status, truck routing, and precision docking. Some of these systems are already available in today's vehicles.

### THE NEED FOR ITS INTEGRATION

While these various collision avoidance and traveler information systems have the potential to provide useful information to the driver, they can decrease vehicle safety if they are not designed and implemented in a manner that is not consistent with driver capabilities, limitations, and expectations. For example, multiple, non-integrated CAS and ATIS displays have the potential to overload the driver's ability to properly perceive and comprehend the information being presented.

Table 1 lists the kind of in-vehicle information that can be presented with CAS and ATIS. Each topic in the table represents a medium to large set of potential messages. The total number of potential in-vehicle driver messages for all the topics in Table 1 would form a list of over forty pages. Furthermore, the manner in which each potential message could be displayed (e.g., sensory modality, display location, message priority, etc.) adds considerably to the total amount of potential in-vehicle information. It is well-known that reaction time and accuracy of human response depends upon the potential message set, rather than only upon the actual message presented (see Kantowitz & Sorkin, 1983, chapters 2-6 for elaboration of this point). Since Table 1 represents a large potential message set, there is ample room for

human delay and error in responding to any such in-vehicle message.

**Table 1.**  
**Potential ITS In-Vehicle Information**

<ul style="list-style-type: none"> <li>• <b>Collision Avoidance:</b> <ul style="list-style-type: none"> <li>– Road Departure</li> <li>– Rear End</li> <li>– Lane Change/Merge</li> <li>– Intersection</li> <li>– Railroad Crossing</li> <li>– Drowsy Driver</li> <li>– Automatic Cruise Control</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• <b>Advanced Traveler Information Systems:</b> <ul style="list-style-type: none"> <li>– Trip Planning</li> <li>– Route Guidance</li> <li>– Route Selection</li> <li>– Multi-Modal Coordination</li> <li>– Route Navigation</li> <li>– Yellow Pages</li> <li>– Automated Tolls</li> <li>– Motorist Services</li> <li>– Personal Messages</li> <li>– Vehicle Status</li> <li>– Regulatory Information</li> <li>– Travel Advisories</li> <li>– Road Condition</li> <li>– GPS</li> </ul> </li> </ul>
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This sensory and perceptual overload can lead to cognitive confusion which would result in a decrease in effective driver performance of the primary task of driving the vehicle. With the driver being exposed to just a subset of the information listed above under collision avoidance and ATIS, the driver can easily be overwhelmed with information to where the information becomes at best, a mere distraction, and at worst, a distraction that takes the driver's attention away from the critical points in the driving task. To be effective, this information must be categorized and prioritized by the system prior to presentation to the driver if the system is to be safe and efficient. An issue that confronts the designers of sophisticated computer-based user support systems such as airplanes and nuclear plants is overwhelming the operators with information (Kantowitz & Casper, 1988; Kantowitz & Campbell, 1996). In the same manner, the vehicle designer must be able to convey to the driver which displays are primary, secondary and tertiary so a number a displays do not compete for the visual and cognitive attention of the driver. An example of a potentially hazardous driving situation could be represented by a driver who is tracking his progress on a route guidance device when his engine oil light illuminates. The driver immediately begins to slow down and initiates a merging maneuver to get to the right hand shoulder. Simultaneously, the collision avoidance system advises the driver of the vehicle in the 4 o'clock position that may be struck, while secondary warnings are reminding the driver of the critical nature of the

loss of oil pressure. In addition, the route guidance system is now beginning to provide advisories that the right merge maneuver is not part of the planned routing. For these systems to function in a safe and efficient manner, they must be integrated at the vehicle level.

The discipline of human factors plays a critical role in the development of safe and efficient in-vehicle information systems. It follows the human-centered approach which essentially means that system design is predicated on user requirements, capabilities, and limitations. For instance, in reference to an in-vehicle information systems, human factors practitioners considers such questions as:

- What information do drivers need and want?
- When should the driver receive the information (i.e., message prioritization)?
- What format should the information take?
- How long should the information be displayed on the in-vehicle display?
- Which of the driver's sensory channels should be used to convey the information?
- What kind of control inputs are necessary?
- How does the current piece of information relate to other pieces of information the driver has already received?
- How does accuracy of the information affect usage and performance?
- How does the information affect the driving task?
- When and how can the driver share processing time between ATIS tasks and conventional driving tasks?

Human factors promotes the development of well-designed, fully-integrated IVIS, which filter, prioritize, and communicate driving-related information. To enable the proper integration of driver and in-vehicle information features, human factors must address a variety of issues on multiple levels (e.g., system, driver, delivery, infrastructure, research methodology, and outreach). The following discussion will focus on some of those human factors issues related to in-vehicle information systems.

## **DEFINING IN-VEHICLE SYSTEM INTEGRATION**

From a human factors perspective, integration is defined by system characteristics and their effects on the driver. Thus, while a control engineer could easily create a list of system characteristics, such as hardware, software and functions, this list would be

incomplete as far as depicting system integration because it does not include effects on the driver. Such driver effects would include workload, compatibility, and might be sufficiently complex to require formulation of a driver mental model (e.g., Levison, Kantowitz, Moyer, & Robinson, 1998, in press). System integration can be achieved only when both the characteristics of the driver and the hardware/ software provided by the system manufacturer are included.

### **Operational Definition of Integration**

The use of the word "integration" among ITS professionals can often lead to ambiguity and sometimes to misunderstanding because it is used by different people to mean different things or it can even be used differently by the same person in different contexts. The word can be employed in regard to separate areas such as hardware, software, infrastructure, user functions, or can refer to the inclusion of two or more of these areas. Within these areas, integration can refer to the subtask, task, subsystem, system, or multiple system levels. Since the use of the term "integration" can cause confusion, a human-centered operational definition of "integration" follows. Within this context, integration is said to be complete when the user perceives one information system. Integration in this paper will be concerned primarily with driver IVIS functions and will be viewed from the perspective of the driver. For now, a laudable goal would be to have drivers perceive all in-vehicle information as emanating from one system.

### **ATIS Guidelines as System Integration**

Integration of in-vehicle systems is a challenge for designers because they often find it difficult to determine the effects of the system on the driver until after the system has been built and deployed. By then it is too late to alter system characteristics and so better integration must await the next revision of the system. Even then, it may not be practical to change aspects of the system that reduce integration due to a desire to retain as much as possible from the first version of the system so that the next model can be deployed as quickly and economically as possible.

However, the human sub-system has known characteristics that can be anticipated during system design. Designers can use this knowledge to improve their systems before the systems are built. Human factors design guidelines for ATIS (Campbell, Carney

& Kantowitz, 1998) and CAS (Lerner, Kotwal, Lyons, & Gardner-Bonneau, 1996) are important tools for system designers.

In particular, the ATIS guidelines were developed over a five-year period and are built upon comprehensive task and function analyses, analytic and empirical evaluation of driver acceptance, and substantial new laboratory and on-road empirical studies focused on the needs and capabilities of drivers who use ATIS in their vehicles. By following these human factors guidelines, the designer has automatically accomplished significant first-level integration within the ATIS devices. Unfortunately, there are not yet existing guidelines for higher level integration, e.g., how should ATIS and CAS be combined within a vehicle? Such guidelines are badly needed and should be a high priority for future research.

### **Levels of Information System Integration**

As implied above, drivers of the future will have access to a wide variety of information subsystems. For these subsystems to be effective, the information within each of subsystems will need to be consistent with each other and with the world on the other side of the windshield. Table 2 contains a conception of the levels as well as selected elements at each ITS information level. The following subsections describe some of the integration issues at different levels starting at the highest information level (i.e., the system level) and proceeding to the lowest level (i.e., the subtask level). As we proceed down through the various information levels, we will only expand on the top element in each information level. (See Table 2 for graphic representation of the ITS information levels.)

**System Level** - Travelers will access information from various sources that represent a variety of media and modes. Within a given day, travelers might obtain information from such sources as kiosks, personal computers (at home or in the office), in-vehicle displays while stopped, parked, or in-transit, and variable message signs on the highway. When appropriate, it is important that such aspects as terminology, data presentation and format, input method, and symbology be consistent and supportive or, at a minimum, non-interfering, to provide the appearance of one system to the user.

**Subsystem Level** - Drivers will have access to a diversity of in-vehicle information categories. Navigation information could include area maps, turn-by-turn directions, and time-to-arrival estimates.

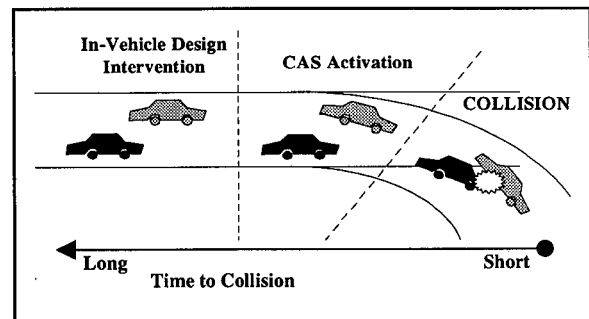
**Table 2.**  
**Examples of Elements Across Information System Levels**

ITS Information Levels				
<i>Subtask</i>	<i>Task</i>	<i>Component</i>	<i>Subsystem</i>	<i>System</i>
• Selection criteria preferences	• Route selection	• Navigation	• ATIS	• In-vehicle
	• Route following	• Routing	• Safety	• Kiosks
• Destination entry	• Route re-selection	• Real-time traffic congestion	• Convenience	• Portable computer
• Route confirmation			• Collision avoidance	• Variable message signs
• Select map scale				• Cell phone
		• Safety advisory		• On-the-road signage
				• Highway advisory radio

Safety oriented information might provide the driver with knowledge of vehicle stability, vehicle diagnostics, obstacle/pedestrian detection, and cargo status. Convenience oriented information could present information as transit schedules, toll collection transactions, weather, and “yellow pages” contents. These subsystems must be integrated with the driving environment to determine when the driver can receive the information. That is, should the driver be able to access information about restaurants in heavy or light freeway traffic or should the driver be restricted to using that function while parked?

An important aspect at this level involves integrating two or more subsystems. Crash avoidance information and other in-vehicle information subsystems can be optimized individually. However, this is done at the peril of driver acceptance of the entire system. Gagné (1962) pointed out that when subsystems are optimized independently of each other, the total system may very well be suboptimal. Figure 1 illustrates the sequence of in-vehicle information subsystems. Early in the sequence we have a traffic advisory information later followed by collision avoidance information. The former subsystem may very well have an affect on the latter subsystem. The more poorly designed the traffic advisory information system is, the more the collision avoidance subsystem will be activated. Frequent activation of the collision avoidance system may affect driver acceptance of such subsystems and/or acceptance of the totality of the subsystems. In other words, frequent activation may be considered a nuisance even though the information provided by the subsystem/system is highly safety relevant. It would be unfortunate, and most improbable, if drivers were

to accept the fact that weaving in and out of one's lane is the price one has to pay for using a traffic advisory information system.



**Figure 1. The influence of a traffic advisory information subsystem on a collision avoidance subsystem.**

**Component Level** - When using navigation systems, there is a variety of subsystems to consider. For instance, drivers can obtain information on navigation, routing, real-time traffic, and safety advisories and warnings. At this level the integration concerns are the uniform ways of reporting the information and prioritization of messages as well as interrelating the information between subsystems. That is, routes that are suggested by the system and accepted by the driver should, in a fully developed subsystem, take into account real-time traffic conditions and safety advisories thus providing the driver with a consolidated understanding of the current situation.

**Task** - Providing routing information involves several potential tasks. Among these are selection of

route, following route instructions, and reselection of route in instances, for example, when there is an accident ahead. The emphasis at this level is on designing the task sequences so that the individual and combined tasks don't take an inordinate amount of time to complete and that they flow logically requiring little or no effort to know where the driver is in the task sequence.

**Subtask** - Selecting a route includes several aspects. For instance, the driver might have to choose selection criteria (e.g., minimal time, shortest distance, or avoid freeways where possible), enter destination and possibly interim destinations, and confirmation of selected route. As in the previous level (i.e., the task level) these subtasks must be integrated so that they do not take an inordinate amount of time to complete and that they flow logically requiring little or no effort to know where the driver is in the subtask sequence.

## SAFETY AND SYSTEM INTEGRATION

One problem in using accident databases to determine highway safety is that accidents are binary events: on any given trip an accident either did or did not occur. This implies that any trip completed without an accident is a safe trip. However, from a human factors perspective, error is a graded set of probabilities. Thus, it is more useful to speak of safety gradients or safety margins rather than a binary classification. An alcohol-impaired eighty-year old driver who is not wearing his eyeglasses driving 100 mph at night in a station wagon might be lucky enough to travel from point A to point B without an actual accident, but this good fortune does not imply that the safety margin for that trip was infinite.

Figure 2 shows that safety margins are derived from two opposing components. As the driver and the vehicle are more capable, the safety margin increases. As the driving environment becomes more demanding (e.g., increased traffic, poor visibility, marginal highway geometry), the safety margin decreases. Thus, the safety margin is a dynamic sum that reflects the aggregate of its two components. When the safety margin is negative, accident probability is high.

While Figure 2 is conceptually interesting, it provides little direct assistance to ITS designers. Figure 3 is a more helpful elaboration of the safety margin concept. It states that drivers have to process two streams of information concurrently. Out-of-vehicle roadway information allows the driver to evaluate the demands of the external driving

environment. However, the driver must also process in-vehicle information which, given the potential for a large ITS message set (Table 1), can be substantial.

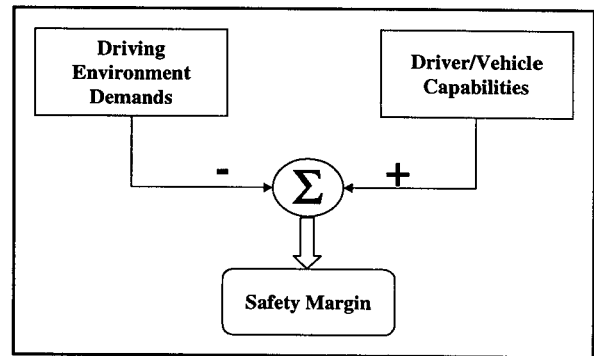
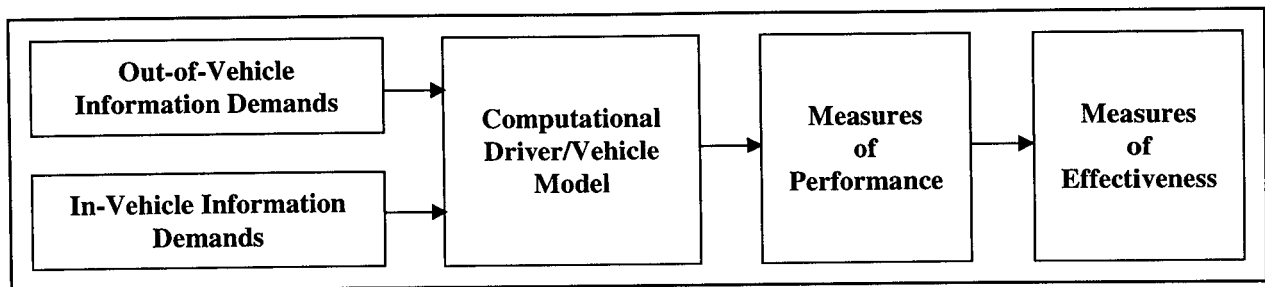


Figure 2. Safety is more than crash avoidance.

The interaction of these two streams of information within the mind of the driver is complex and difficult to characterize by only qualitative description. Designers need detailed answers about sub-system trade-offs and these are best provided from a quantitative computational model of the driver and vehicle (e.g., Levison et al., 1998, in press). Such a model then generates measures of driver/vehicle performance for specific combinations of roadway conditions and in-vehicle information loads. But even these measures are not sufficient to aid ITS designers. Knowing that the standard deviation of lane positions increases by .8 feet or that driver reaction time increases by 112 msec can help the designer make relative judgments but unless the designer knows the implications of such judgments for safety, it is still hard to make absolute design decisions. Measures of performance must be translated to measures of effectiveness (Dingus, 1998, in press). If a system designer knows that a certain increase in lane position standard deviation can be related to probabilities of a vehicle incursion into an adjacent lane (Allen, Parseghian, & Stein, 1996) that a secondary-task reaction time can be translated into a probability of a fatal accident (Harms, 1996), then meaningful trade-offs can be established. Without the kinds of calculations and translations shown in Figure 3, the safety-margin concept remains vacuous and of small practical utility.

Finally, we must also remember that all the items inside a vehicle have the potential to increase driver workload, even if they are not part of the specific ITS items being designed. So-called convenience items, such as radios and cellular phones, also affect the safety margin by providing





**Figure 3. Safety is a system characteristic.**

increased demands of in-vehicle information. In a fully integrated system, all these devices would be interconnected and messages would be prioritized and regulated to prevent driver overload. Until that happy day, ITS designers must leave some safety margin for the driver to process in-vehicle information from non-integrated in-vehicle systems.

While a major ITS goal is to increase the safety margin, paradoxically, new advanced technology if poorly implemented can have the opposite effect and make driving more dangerous. The driver can process much less information per unit time than technology is capable of presenting. A system designer who tries to maximize the information his system sends, perhaps in order to obtain a competitive advantage over other ITS products, may be decreasing the safety margin. While human factors experts understand driver limitations in a general way, much more specific research is badly needed before we can safely incorporate convenience items and new ITS technologies inside vehicles. Research on human factors will allow system designers to aid drivers using advanced in-vehicle technologies without decreasing safety margins.

## ACKNOWLEDGMENT

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### ABSTRACT

This paper examines copilotting as a strategy used by older drivers to compensate for some of the age-related deficits in driving skills. It also reports on an exploratory study that found that older drivers consider help of the human copilot useful in ITS navigation systems. Little is known about copilotting and since knowledge about this behavior would be valuable in developing ITS systems for older drivers, research into this topic is needed.

### INTRODUCTION

Driving and navigating an automobile become more difficult as people age. There is deterioration of vision, particularly at night as sensitivity to glare increases, as well as an increase in reflex and reaction times (1). There is also a reduction in attention resources, which leads to reductions in cognition and perception (2). As people age, the ability to divide attention between several tasks decreases (3, 4), as does the ability to ignore irrelevant information (5, 6). Many studies indicate that the deterioration of cognitive processing due to aging has an effect on spatial ability, navigation, and way-finding skills (e.g., 7 - 11).

The elderly are the fastest growing portion of the population of the United States and the percentage of older drivers on the roads is steadily increasing. The percentage of licensed drivers who are over 70 years of age has increased from 3.9% in 1965 to 9.3% in 1994 (12, 13). Furthermore, in 1994, 75% of all adults between 75 and 79 years of age, about 62% of those between 80 and 84, and 40% of those over 85 held driving licenses. (13). These proportions are expected to increase as the "baby boomer" cohort continues its lifecycle.

An automobile in American society provides not only transportation but is important in maintaining one's independence, autonomy, and in some cases, self-esteem (14). Curtailment of driving usually means relying on others for transportation, incurring the inconvenience of public transportation, reducing trip making, and decreasing involvement in other activities. It is, therefore, not surprising that older drivers continue to drive as long as they can even though their driving skills may be diminishing. However, older drivers do employ various strategies to compensate for the effects of aging on their skills. They avoid situations that they feel are dangerous, difficult, or stressful such as driving at night, in bad weather, on limited access highways, and in unfamiliar areas (e.g., 15 - 17). They also drive more slowly and cautiously. Another strategy used by older drivers is to copilot or enlist the resources and abilities of another person

in piloting and navigating the vehicle.

Recent technical advancements in the field of Intelligent Transportation Systems (ITS) hold great promise for the older driver. Systems such as in-vehicle navigation and route guidance, collision avoidance, near-object detection, intelligent cruise control, and night-vision enhancement may be able to extend the time some older drivers can safely and securely operate an automobile (18). However, it is also possible that such systems can offer more distraction and confusion and make driving even more difficult for the older driver. Whether such systems help or hinder depends on how well the needs, preferences, and abilities of the older driver are taken into account in the development and design of these systems.

The copilotting activity of older drivers appears to be a behavior that could provide valuable input into the design of ITS systems for older drivers. In-vehicle navigation systems and route guidance, in particular, are types of copilots and it seems reasonable that lessons learned from human copilotting would be useful in their development. Yet, little is known about the human copilotting practice and it has not been a consideration in ITS designs.

### OLDER DRIVER NAVIGATION

What is known about the navigating and piloting performance of older drivers comes from examination of driving and navigation performance of solo drivers conducted as part of the process of developing ITS in-vehicle navigation and route guidance. Studies that compared driving and navigating performances of older drivers using standard navigation aids such as maps and written instructions against various ITS in-vehicle navigation systems, generally confirm that older drivers do not perform as well as younger drivers. These studies also find that the performance of the older drivers improves when using ITS in-vehicle navigation systems as compared with using maps or written instructions (19, 20).

Human-factors studies of ITS in-vehicle navigation have found that older drivers spend significantly more time looking at navigation displays than younger drivers (21, 22). This raises safety concerns because older drivers have been found to need to view the road for a greater percentage of time than younger drivers to maintain vehicular control (23). Walker et al. (24), studying driving and route following performance with additional task loads, found a very strong age effect on the Increase of driving performance deficits with heavy task loads. They found that magnitude of the age difference was reduced when the navigation information

was presented via auditory instructions. While this has important implications for ITS in-vehicle navigation system design, it should be noted that hearing loss is extremely prevalent among older adults (25).

A recent study by Barham et al. (26) found that the overall standard of driving by a sample of drivers over 65 years of age, driving an unfamiliar vehicle equipped with an in-vehicle navigator in an unfamiliar area, was not adversely affected by the route guidance system. However, for a portion of the subjects, there was some deterioration of performance when faced with the dual task of driving and following the route guidance system's instructions.

The results of these studies indicate that the driving performance of older drivers is helped by in-vehicle navigation systems. However, they also provide evidence that some portion of the older drivers have problems hearing, seeing, and processing the information coming from an in-vehicle navigation unit.

## COPILOTING

I was part of a research team that noticed the use of copiloting by older drivers using ITS in-vehicle navigation systems. We were conducting two natural use studies of in-vehicle navigation systems as part of an evaluation of the FAST-TRAC ITS project in Oakland County, Michigan (27, 28). In these studies, subjects were given project vehicles equipped with in-vehicle navigation devices to drive for one month and instructed to use them in their normal every-day driving. The subjects kept driver's logs of their trips and completed a detailed survey about their perceptions and valuations of the systems.

The two in-vehicle navigation systems were the Ali-Scout and TetraStar systems, both made by Siemens Corporation. In the Ali-Scout system, the vehicle's navigation unit communicated with a central computer via a system of roadside beacons. The TetraStar system was a stand-alone system that used GPS technology and map matching to provide guidance. Both systems provided visual and voice turn-by-turn guidance to destinations specified by the user.

A two-factor experimental design, with three age categories (19-to-29, 30-to-64, and 65-to-80) and the two sexes, was used in both natural use studies. In the first study, 102 subjects drove a project vehicle equipped with an Ali-Scout system for a month. In the second study, 60 of the original 102 subjects drove a project vehicle with the TetraStar system for one month. The differences in users' perceptions and behaviors toward the two navigation systems are reported elsewhere (28).

Analysis of the experimental data showed differences in the way the older drivers used the navigation systems, as compared to the two younger groups of drivers. Older driver trip patterns were different; they traveled at different

times of day; and they tended to make more recreational trips than other drivers. They also had more problems learning and understanding the systems. However, once the oldest group of subjects learned to use the navigation units, they used them more than other drivers.

Investigation of copiloting practice was not part of the original study. However, in the interactions with the subjects, we noticed that the older drivers were likely to team up with their spouses or companions when learning and using a system. The involvement of this second person was much more evident in the oldest age group than in the two younger groups. The older drivers also tended to comment more about the location of the navigation displays, the glare on the displays, and the difficulty in seeing some of the information on the displays. It was clear that older drivers had some unique problems, requirements, and uses of in-vehicle navigation systems.

We decided to look more closely at this teaming or copiloting activity. A search of the literature revealed little. We found that copiloting was mentioned in a study of the driving behavior of persons suffering from Alzheimer's disease (29), where drivers were totally dependent on their copilot for directions and even the interpretation of traffic control signs and signals. We also inferred support for copiloting from a study of older drivers and an ITS navigation system conducted in a simulator by Mollenhauer et al. (30) where in post-experiment debriefings, subjects revealed that they rarely drove to unknown destinations by themselves. We interpreted this to mean that the older drivers prefer to make such trips with another person, or copilot.

To further explore this phenomenon, we invited the older subjects, who had participated in both natural use studies, and their spouses for group interviews to discuss how they drove when they drove alone and together, how this changed over time, and how they used the ITS navigation units. In all, 18 people participated. Their ages ranged from 64 to 82 with an average age of 72.2.

The group interviews indicated that the older subjects often used a copilot to help them overcome the challenges experienced in driving. The copilot served a number of specific functions that are consistent with the changes in perception and cognition that older persons experience as they age. One of the most common uses of a copilot described by our discussion participants was that the copilot served as "an extra set of eyes" for the driver to scan the environment for navigation cues, (e.g., landmarks, road signs) that were useful for the driver.

The discussions also indicated that copilots helped drivers compensate for declines in reaction time and increased difficulty with divided-attention tasks. The copilots provided the driver with information earlier than would be available without the copilot, thus reducing the negative impacts of increased reaction times. Put simply,

the copilot may have increased the amount of time available for making a decision. The copilot also served as a second conduit of information, reducing the need for the driver to engage in divided-attention tasks. The copilot paid attention to tasks that the driver may otherwise have had to attend to, thereby reducing the attentional load required from the driver and freeing the driver to focus on the driving. The companionship function of the copilot was also frequently mentioned as an important role for the copilot.

We found that ITS in-vehicle navigation units used in our natural use studies served as copilots for older drivers to a certain extent, much like human copilots do currently. Discussion participants reported that they thought that an ITS unit was almost as good as a human copilot, but most agreed that an additional human copilot was helpful in using the ITS navigation unit. When present, it was the human copilot who monitored the navigation unit.

## FUTURE DIRECTIONS

Copiloting, appears to be a compensatory behavior used by older drivers to help them overcome some of the deleterious effects of aging on driving and navigating vehicles. However, very little attention has been given to this behavior and the effects that copiloting may be having on the mobility of older persons are not fully understood. Since ITS technology is attempting to serve some of the copiloting functions, questions related to the "who, how, when, and where" of copiloting need to be answered.

Older drivers may in large part be more eager to have both the ITS unit and a human copilot together because of added difficulties associated with seeing, hearing and interpreting the information presented by the ITS unit. The human copilot provides another set of eyes and ears to perceive and interpret information presented by the ITS unit. In addition, while ITS navigation units may be able to present information to the driver, a human copilot provides a decision assist system that current ITS products cannot. The human is flexible, can respond to driver queries spontaneously and can adjust more readily and quickly to the driving and information-processing style of the driver.

ITS navigation systems can either replace or supplement copiloting functions of humans. Current evidence for older drivers indicates that the preference is for supplementing human copilots. As such, it is important that the design of such systems for older drivers consider the copiloting environment.

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### **ABSTRACT**

Visual enhancement studies have traditionally focused on traffic situations with seriously degraded visibility conditions, such as night traffic and driving in fog. Based on accident statistics and theoretical considerations it is argued in this paper that it would probably be better from a safety point of view if the study of visual enhancement were concerned primarily with normal, good visibility conditions. Visual enhancement is however, also needed in situations with impaired visibility. Then it is better to improve direct visibility (e.g., by lighting) than to improve visibility indirectly (e.g., by radar), because in the former case the advanced human visual system may be used to its full capacity.

### **TRADITIONAL ENHANCEMENT OF VISUAL CONDITIONS**

Traditionally (if one may talk about tradition in such a modern topic) visual enhancement means improving existing driver visibility conditions where visibility is seriously impaired. That is to say create visibility in situations where visibility without special support is very bad. Such situations include on the one hand, driving in degraded the atmospheric conditions such as fog, heavy snow and rain, or smoke. On the other hand, it includes driving in darkness, what we normally call night driving on nonilluminated roads. Combinations of these conditions are even more serious than each single one. Night driving is the most common situation in which the visual conditions obviously need enhancement.

If we stretch the concept of visual enhancement a bit we will find that drivers' visual status also comes into the picture. For instance, old drivers with degraded vision sometimes need visual enhancement in situations where other drivers have no need. Other drivers with visual diseases, such as cataracts, have much more need for visual enhancement than drivers with good visual status.

### **THE NEED FOR VISUAL ENHANCEMENT ALSO IN GOOD VISIBILITY CONDITIONS**

It is argued here, however, that we should expand the concept of visual enhancement far beyond

the traditional degraded visual situations. Visual enhancement, especially the conspicuity of other road users, is needed at least as much in normal driving situations without any visibility impairment. To begin with, there is much more traffic in daylight and therefore about two-thirds of the accidents happen in daylight. The other arguments presented to support such an expansion into normal situations are elaborated on in the following sections.

### **Driver Explanation of Collisions**

If we analyse driver reactions and explanations after most vehicle collisions we will find that by far the most common explanation for the collision is that one or more of the involved drivers claim that they saw the other road user (vehicle, motorcycle, bicycle or pedestrian) too late or even not until the collision was a fact. Late detection of vehicle coming from an unexpected direction is in fact the most basic driver error (Rumar 1990). There may be other more complex errors and higher-order errors later in the process. But without timely detection and recognition, the probability of a collision is high. Enhancement of the conspicuity of other road users consequently would play an important role in this process.

### **Unnatural Detection Situations**

If we analyse the driving task from an ecological point of view, we will find that our senses were developed for situations quite different from those we are facing as drivers today. Our ancient enemies, mainly predators and other humans, attacked us in a dynamic way exhibiting motion patterns to which we are still very sensitive. Our modern enemies, mainly cars, "attack" us in a motionless manner. They just slowly grow on our retina without any apparent motion. This is a situation to which our senses are not sensitive. We would benefit from some kind of visual enhancement. The significant reduction of daytime collisions as an effect of the so-called daytime running lights is a good illustration of this (Koornstra et al. 1997).

### **Field of Free Driving**

One of the earliest, and still one of the best, driver models formulated is based on driver visual

perception. Gibson and Crooks presented a model (1938), which states that one of the main tasks of the driver is to create in front of him an area of free driving. This area is of course heavily dependent of how the driver perceives the position and motion of other road users -- in other words how conspicuous they are and how their continued motion is predicted. Of course, enhanced conspicuity of the other road users and their paths is an important part of the task to create such an area of free driving.

### **Automatic Driving**

Other driver models (e.g., Rumar 1990) state that driving of an experienced driver is self paced and basically automatic. The driver predicts what will happen and bases his actions on those predictions. Otherwise the driving process would be very slow and jerky. Only if the predictions turn out to be erroneous does the driving process become conscious and meditated as well as slow. Visual enhancement, especially of the other road users around the driver, should facilitate veridical predictions and thereby keep the driver reactions on a quick and automatic level.

### **Target Characteristics**

The character and motion pattern of other road users should be enhanced in addition to their conspicuity. For instance, an oncoming car looks very much the same if it is running at a speed of 50 km/h as if it were moving at 100 km/h. However, in a situation when overtaking another car is considered, this difference in speed may be very dangerous. Studies have shown that drivers tend to estimate the meeting point to be half way between the two approaching cars (Norling 1963). In other words, the speed, the course, the energy of other road users could be visually enhanced. Yes, even the intentions of the other road users could be presented to the driver.

### **Two Visual Functions**

Leibowitz and Owens (1977) postulated that there are two main visual functions involved in driving. One is mainly concerned with foveal vision and deals with detection and recognition. The other one deals with visual guidance and orientation and is mainly carried out in peripheral vision. Leibowitz and Owens argue that one of the main reasons for the high accident rate in night traffic is that drivers largely maintain their guidance vision while recognition vision is impaired. Therefore they underestimate the visual problems in

night driving and drive too fast.

The same argument could in fact be applied to daytime driving. Drivers have an excellent visual guidance and are not aware of the fact that their recognition vision is far from perfect. The collision-reducing potential of daytime running lights is again a good illustration of the imperfection of recognition vision even in broad daylight. Consequently, visual enhancement of other road users to improve driver-recognition performance should be good.

### **VISUAL ENHANCEMENT IN CONDITIONS WITH IMPAIRED VISIBILITY**

This expansion of the need for visual enhancement into the region of normal driving in no way reduces the need for visual enhancement in impaired visual conditions such as fog, falling or whirling snow, heavy rain, smoke, or darkness. In one way, visual enhancement in impaired-visibility conditions is different from visual enhancement in normal visibility conditions. In degraded-visibility conditions, there is an obvious need also to enhance the visibility of the road itself, not only other road users and other obstacles. This need is, as was stated above, considerably smaller in normal visibility conditions.

Judging from the hypothesis mentioned above presented by Leibowitz and Owens (1977) it is, however, questionable if visual guidance should be enhanced when in degraded visual conditions. Rumar (1990) presented ideas along the same line when he stated that driving is a self-paced task. Maybe the self pacing is made primarily on the basis of visual guidance.

There are studies recommending that we should be cautious with improving visual guidance in night driving too much. That might even lead to impaired safety. Kallberg (1993) showed that improving visual guidance at night by means of retro-reflective side-post delineators was followed by an increase of speed and an increase of injury accidents.

Initially it was mentioned that visual enhancement could even be personal. The idea could be compared to tailoring the controls of a car to the specific disability of an individual driver. The same could be done for drivers with some visual impairment. Such an application could very well be the initial step in the introduction of visual enhancement because the number of cars to treat would then be limited.

## **PROBLEMS ASSOCIATED WITH VISUAL ENHANCEMENT**

There are a number of problems associated with visual enhancement independent of whether the driving situation is normal or particularly difficult from visibility point of view.

### **Unbalanced Visual Enhancement**

If some stimuli or some characteristics of specific stimuli are enhanced, it implicitly means that some other stimuli or that some other stimuli are not enhanced, or at least not enhanced as much. In other words, the natural relation between the intensity of various visual stimuli is changed. Now if that is done in a correct way, balancing the stimuli intensity between the various stimuli, it is exactly what we would like visual enhancement to do -- enhance the whole scene. But if it is done by increasing the intensity of one group of stimuli at the expense of another group, it may cause serious conscious or unconscious misunderstandings in the driver and result in behavioral errors.

The previously mentioned results from studies of the safety effects of retroreflective side-post delineators in Finland (Kallberg 1993) indicate this risk. The enhanced visibility of the road, the improved visual guidance, made the drivers increase their speed and thereby decrease their safety instead of increasing it. One explanation of these results is that the visual guidance of the road was enhanced but the visibility of obstacles and road surface was not enhanced. The existing unbalance was enhanced.

### **Direct and indirect visual enhancement**

Visual enhancement may be achieved by enhancing the direct-visibility situation (e.g., by improved vehicle lighting or by daytime running lights) or by enhancing the targets indirectly (e.g., by infrared light or radar). In the first case (direct enhancement) the human visual system and visual processing are used in the traditional way. The targets out there are just made more visible. They still compete on the same playing ground.

In the second case (indirect enhancement) the rays that enhance the scene in front of the driver are not visible to the human eye without any support or amplification. Either the driver will have to wear special glasses or he will have to watch a screen or a

display. This is a weak point in such designs. Even if the image is projected on the windshield in the line of vision of the driver (by means of head-up displays, or HUD) it may compete in a distracting way with the external stimuli in the traffic scene. If the image is not projected in the line of sight of the driver, he has to move his eyes from the traffic scene, and the distraction risk is obvious. In indirect visual enhancement, the targets do not compete on the same playing ground.

Furthermore, the system safety (technical reliability) will most probably be considerably smaller in systems based on indirect visual enhancement. Another problem with indirect visual enhancement is that it will have to solve the impossible problem of choosing between false alarms and detecting misses. Also, the integration of visual enhancement systems with other advanced intelligent transportation system (ITS) in the car would be much more simple if visual enhancement would be based on direct vision enhancement. System integration is in fact an overlooked but very serious problem in the future development of ITS.

## **CONCLUSIONS**

The first conclusion is that visual enhancement is probably more needed in normal driving conditions than in situations where the visual conditions are impaired.

The main reasons are:

- Normal visibility conditions are much more common and therefore most of the accidents happen in normal visibility situations.
- Drivers claim late detection as the main reason for daytime collisions.
- A number of theoretical arguments support this idea.

The second conclusion is that visual enhancement is a delicate task where it is very important that the balance between the various stimuli and targets must not be unduly disarranged or even enhance. Then safety may be reduced instead of improved.

Furthermore, direct visual enhancement seems to be far superior to indirect visual enhancement. The direct visual enhancement makes full use of the fantastic analysing capacity of the human visual system and avoids the potential risk of hazardous distraction and difficult system integration.



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### INTRODUCTION

Over the past 100 years, the motor vehicle has had enormous influence on economic growth and social development. However, the motor vehicle has also produced social ills. It continues to be a major cause of death and injury and this is expected to increase as the level of motorization increases in established as well as emerging economies. By the year 2000, it is projected that there will be one traffic fatality and 50 injuries per minute on the world's roads. Thus, motor vehicle safety is an urgent global issue.

It is widely acknowledged that human factors are implicated in 70-90% of motor vehicle crashes. Traditional approaches to human factors research emphasized the driver as a system component. The early emphasis on human-machine cybernetics reflected a view of driving as a continuous closed-loop process. Control-theoretic models were proposed in an effort to optimize overall vehicle performance. Later refinements incorporated concepts of open-loop driving; however, the primary task of the driver remained the control of vehicle speed and lane position.

In recent years, automotive technologies have reflected advances in information and communication technologies. The intelligent driver interface (IDI) is a good example of an area of application receiving a great deal of attention in Europe, Japan and the USA. IDI's are being developed to incorporate features such as, vision enhancement, active steering and braking, adaptive cruise control, adaptive dynamics, route guidance, driver performance monitoring, collision warning systems, warnings of running-off-the-road, and other systems. They will present more information, incorporate more functionality, offer better user support and require more user interaction.

Near-term ITS will continue to require the active participation of the driver. Some critics contend that on-board systems will prove too complex, too demanding, and too distracting for users. They argue that intelligent technologies can lead to loss of skill, increased driver error, and, as a consequence, lead to greater risk of collision.

A major feature of Transport Systems (ITS) concepts is the close coupling of vehicle and infrastructure elements in an effort to achieve environmental and mobility benefits. That is, on-board systems will rely increasingly on the integrity of

vehicle-highway communications and information received from external sources (such as traffic control centres). The implication is greater emphasis on macroergonomics considerations.

Although the role of human factors in system effectiveness and safety is widely acknowledged, there is little evidence of the application of human-centred approaches in modern designs. It must be clearly understood that technology itself is not inherently beneficial or detrimental. Safety depends on the design and functionality of the interface and its integration with other elements of the system. In other words whether new technologies will succeed in solving our future transportation problems or not depends primarily on human factors.

Intelligent driver interfaces will increase the complexity of the driving task and create the need as well as the possibility for adaptive technologies. On the one hand, new technologies expand the solution space beyond conventional boundaries. On the other hand, the solution selected must be optimized with respect to usability, suitability, safety and user acceptance. Four principle considerations characterize the nature of the problem and, by inference, the focus of future human factors endeavors (Noy, 1997).

#### *Increasing complexity*

The increasing complexity of the interface requires that we understand and develop computational models for complex human-system interactions. We currently lack adequate theory to ensure that IDI designs are appropriate within the context of the evolving driving task. Current efforts to generate human factors design guidelines based on empirical data are important in addressing immediate needs. However, they are inadequate in the medium to long term because they will not yield a coherent body of knowledge of human response and adaptive behaviour in traffic. Computational models based on sound theory would be far more valuable and usable by designers.

#### *Adaptive, friendly interfaces*

The work by Michon (1993) and others have clearly demonstrated the need for driver interfaces that adapt to human and traffic circumstances. Techniques will be required to adapt interfaces to individual

differences in mental models and driving styles. Moreover, the adaptive interface will need to reveal the human side of technology to be accepted and used effectively. Issues such as privacy, trust in system integrity and value, and system usability will require innovative approaches. Finally, stronger societal values favouring inclusion of individuals will increasingly demand that systems be designed to accommodate all drivers, not just 95% of the population. This is most evident in the recent controversy over the risk that current air bag systems pose to short females.

### ***Emphasis on cognition***

The role of driver cognition in traffic safety has been widely recognized for some time. Treat et al., (1979) have performed an in-depth analysis of human causes of accidents. Like other studies of human error, they reported that driver error was involved in 70% to 90% of collisions. However, unlike most studies, their data permitted analysis of the root causes. Their analysis revealed that recognition errors were involved in at least 41% of driver errors and that decision errors were involved in at least 29% of driver errors. All other categories of human errors were minor in comparison to recognition and decision errors. These results signify that limitations in human information processing are the most prevalent driver errors.

Current IDI trends towards greater automation and greater use of information technologies demand much greater emphasis on understanding driver cognitive factors than is currently evident. The proliferation of auxiliary instrumentation (e.g., navigation displays) is especially problematic due to the greater potential for interference between operational-level cognitive requirements and higher-order, strategic-level cognitive requirements (Kantowitz, 1997). A black box model of the human driver is no longer adequate to address the emerging needs of system designers (Thierry et al., 1996). Designers need models of the human information processing system that will predict driver decision-making, situational awareness and strategies for negotiating in traffic. Dialogue management, compatible with driver mental models and based on knowledge of driver cognitive behaviour, is a key microergonomics issue.

### ***Macroergonomics***

Hendrick (1994) describes macroergonomics as a top-down sociotechnical systems approach to human-system interface design. At least conceptually, this

means that all aspects of the transportation systems must be considered at each level of design. For example, from a macroergonomic perspective the design of an in-vehicle information display requires not only optimization of the driver interface but the interfaces of all other persons who are directly or indirectly involved in the generation, transmission and use of the information, including, for example, operators in the traffic control centres, inspectors, system maintainers, and police enforcement officers. The more tightly coupled and integrated the traffic system, the greater the need to get the macroergonomics right. An ITS system may be optimized at the microergonomic level, but if it is not also optimized at the macroergonomic level, it may fail to provide the intended benefits, or worse, it may lead to catastrophic failures.

Macroergonomics, of course, has more far-reaching implications for transportation system design. It implies a re-examination of traffic system objectives and re-engineering system hardware, software, liveware, and institutional elements to better achieve those objectives.

### ***A NEW ROLE FOR GOVERNMENT***

The role of government with regards to transportation system operation is changing. Governments have begun and will continue to transfer their traditional responsibility for providing infrastructure to the private sector, but they will retain the responsibility for planning and overseeing system mobility and safety performance. This change in governmental role will have important implications for human factors R&D. It will create new needs within industry to solve human factors problems and it will focus government R&D efforts on mobility and safety assurance.

With respect to ITS safety, governments will have a dual responsibility; a) to encourage the development of technologies that can enhance safety, and b) to discourage technologies that have the potential to adversely affect safety. Traditional governmental approaches to safety delivery tend to be reactionary (the problem is identified in the field, possible interventions are investigated, cost-benefit analyses are performed) and are considered not fully responsive to the challenges introduced by new technologies. There is increasing recognition of the need for systematic procedures and criteria for testing the systems safety of Intelligent Transport Systems (ITS) prior to large scale market penetration (Noy, 1998).

If ITS safety assurance is to be regulated, then consideration must be given developing new regulatory paradigms. Vehicle safety regulations have evolved from design specific requirements to performance criteria in an effort to remove design restrictions and promote product innovation. However, performance criteria rely on knowledge of system functionality, a precursor which is lacking for ITS since the technologies underlying ITS systems and their functionality will vary among manufacturers and likely to be constantly re-engineered in the foreseeable future.

The ever-changing design of vehicles and its impact on the nature of driving necessitate a new approach for the delivery of motor vehicle safety. It may be necessary to think in terms of intervention at a level higher than performance requirements. At this level, system functionality remains entirely within the domain of the designer. However, the designer must perform prescribed tests to ensure that the system is usable, safe, and acceptable (Noy, in press).

## CONCLUSION

It is not yet clear whether in future years motorization will continue to add value to society or whether in fact it will begin to adversely affect safety, the environment and overall quality of life. While many predict the imminent collapse of the road transportation system, others are strong advocates of technological solutions. The success or failure of future transportation systems depends on human factors having a major role in systems design and implementation. Transportation system design has to be right the first time because of the potentially huge implications of failure. It will be necessary to validate designs against usability criteria to ensure that they are readily understood, can be used accurately and reliably and generally support user tasks.

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# Technical Session 1

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## Advanced Frontal and Offset Frontal Protection

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Chairperson: Claudio Lomonaco, Ministry of Transport, Italy

The International Harmonized Research Activities (IHRA) Status Report of the Advanced Offset Frontal Crash Protection Working Group was presented at the onset of this Session during the 16<sup>th</sup> ESV Conference. This Report begins Technical Session 1.

**INTERNATIONAL HARMONIZED RESEARCH ACTIVITIES (IHRA)  
STATUS REPORT OF THE ADVANCED OFFSET FRONTAL CRASH PROTECTION  
WORKING GROUP**

Claudio Lomanaco  
Ministry of Transport  
Italy

**ABSTRACT**

This paper will provide an overview of the work progress of the advanced offset frontal crash protection group of IHRA. It resumes, including tables and a final flow chart, the strategy of the group to cope with the assigned task. This is the commitment to achieve an harmonised frontal crash protection procedure taking into account the different world wide views in this field.

**INTRODUCTION**

At the ESV Government Focal Point Meeting on International Harmonised Research Agenda held in Melbourne in May 1996, six research fields on passive safety were highlighted as the ones in which harmonisation efforts could be most fruitful. The leadership of future activities in each field was assigned to a specific country. In particular the E.U. accepted the leadership in the field of Frontal Collision Safety.

The aim of the Working group is to develop internationally agreed test procedures designed to improve the car structures in order to cope with the event of frontal collision thus enhancing the level of occupant protection provided in frontal impacts. Such task shall be accomplished defining shared unified injury criteria and, if needed, geometrical criteria on common basis.

There is a shared world wide common term of reference: the collision of two equal cars. Parameters of testing, such as tools, are diverging. Indeed the differences related to the use of different barriers (deformable/stiff barrier) and dummies are substantial. Differences among countries in the selection of testing procedures may be attributed to the different infrastructures and data banks. Thus regulations are diverging as a consequence of these discrepancies.

It has to be remarked that basically two main developing tendencies on frontal collision standard are present:

- 1) In Europe the Parliament has given mandate to the European Commission to review the present Directive on Frontal Collision (Deformable barrier, 40% overlap, impact speed, some geometrical and biomechanical parameters).
- 2) In the USA the Congress has given mandate to NHTSA to go through a short/medium term activity to verify the possibility to finalise a standard which could be harmonised with the European one.

Furthermore, a long term activity has been devoted to the development of a specific USA frontal impact test carried out with a mobile deformable barrier.

**WORK PROGRESS OF THE GROUP**

The analysis of the differences started considering the common and the diverging aspects of the main items. Since the first meeting, the activity in progress devoted to the assessment of the different frontal impact procedures nowadays used in Europe and USA was examined. Such procedures are different in terms of impact speeds and barrier.

During the discussion items and distinguishing characteristics of miscellaneous existing standards, on which activities are in progress, were pointed out, particularly in the USA, where researches using different barrier types with different impact speeds are carried out.

Furthermore this country has remarkably developed in this research activity, the connections among different risks displayed by using dummies different by 50<sup>th</sup>ile male, on which base the vehicle structure is tailored (50<sup>th</sup>ile female and 95<sup>th</sup>ile male dummies).

To this research, Canada get ahead on the topic of the dummy/Air-Bag interaction. On this side Canada has given a great contribution complementary to the US researches.

On the base of such characteristics the work has been splitted in two phases, which are corresponding to the short and long term part of the programme.

**Work programme.**

**1 - 1<sup>ST</sup> Phase (short term programme)**

A board to define the main aspects was drawn by the group members. On each of these the participants of the group engaged their self to develop specific activities and to give out results.

Accordingly, the table with the topics of interest has been established by the group as follows:

**Table 1**  
**Topics of interest**

WORKING MATTER	USA	CAN	EEVC	J	AUS
Trolley	X				
Types of barriers	X	X			X
- stiff	x	x			X
- deformable	x	x			X
Impact angle	X				
Dummy	X	X	X		X
- 5 <sup>th</sup> %ile female	x	x			X
- 95 <sup>th</sup> %ile male	x	x			
Impact speed	X	X	X		X
Performance criteria	X	X	X		X
- footwell intrusion	x		x		X
- steering wheel intrusion	x		x		
- abdomen injury detection		x			
- arm injury		x			
Air-Bag performance	X	X			X
- Deployment time & effects.		x			
Extension to vehicle of category N1.			X		

### 1.1 Commitments

During the discussion, the American delegate declared that NHTSA is planning in the first stage approach to study in the short term the potential benefits of the EEVC frontal test procedure under the US conditions. It appears that the EEVC test procedure may offer advantages to the USA if used with a 5<sup>th</sup>%ile female dummy, based on the dummy transducer readings in some preliminary tests. If the first stage (adoption of a modified EEVC test procedure) proves to have not potential benefit for the USA, the first stage would be abandoned and work would concentrate on the second stage.

EEVC confirmed that is going toward the solution of a fixed barrier getting on legs biomechanical criteria and higher impact speed.

### 1.2 Schedule time

The group devoted to this first phase the scope and the goals, remarking that the work program has to be finalised within five years and it should be set into the following deadlines:

#### 1. ESV Windsor Conference

Presentation of the first report which contains the determination of research specific aspects and the working program launching focused on the drawing up of a technical standard on frontal crash protection.

#### 2. End 1999/beginning 2000

Completion of the technical standard project and validation programme launching.

#### 3. ESV 2001

Work completion and technical standard project presentation to the ESV conference.

### 2 - 2nd Phase (Long term programme)

According to the NHTSA and EEVC work plan and in order to better define the American and the European approaches, the group agreed the bases of a comparative analyses of the advantages of the use of a mobile barrier in the Frontal Offset impact test procedure and the alternative approach to achieve the same advantages with fixed barriers.

The main points of the comparison are pointed out in the following table:

**Table 2.**  
**Trolley-based Frontal Offset Impact Test Procedure**

ADVANTAGES	ALTERNATIVE APPROACH TO ACHIEVE SAME ADVANTAGE WITH FIXED BARRIER
1. Takes into account the effects of the Mass Ratio of the impacting vehicles	Change impact speed with vehicle mass.
2. Can include angular effects on the deformation and intrusion characteristics	No known alternative.
3. Can include a possible measure of Compatibility (by, for instance, measuring the vehicle and/or trolley acceleration	Measure the force on the fixed barrier behind the deformable face.
4. The acceleration pulse, $\Delta V$ and energy distribution is 'correct'.	No known alternative.
DISADVANTAGES	POSSIBLE ACTIONS TO REDUCE THE DISADVANTAGE
1. Complex test procedure for "moving barrier-moving car" (High speed trolley vibrations, difficulties to videorecord impact effects between mobile trolley and car)	Reduce complexity by testing co-linearly and/or using moving barrier to stationary car?
2. Repeatability of more complex test may be poor (for "moving barrier-moving car").	
3. Limited number of test laboratories with capability to perform trolley to vehicle testing.	Investigate
4. Unknown ground and other interaction effects, especially if one vehicle stationary while the other travels at higher speed – to represent both vehicles moving.	?
5. Need to agree on a harmonised barrier mass when vehicle fleet differs.	Agree to differ

### 2.1 Commitments

USA would concentrate on the second stage approach, which regards the Trolley-based Frontal Offset Impact Test Procedure, in case the first one will not produce any potential benefits.

EEVC will undertake the research programme in the second stage, by assessing the following items:

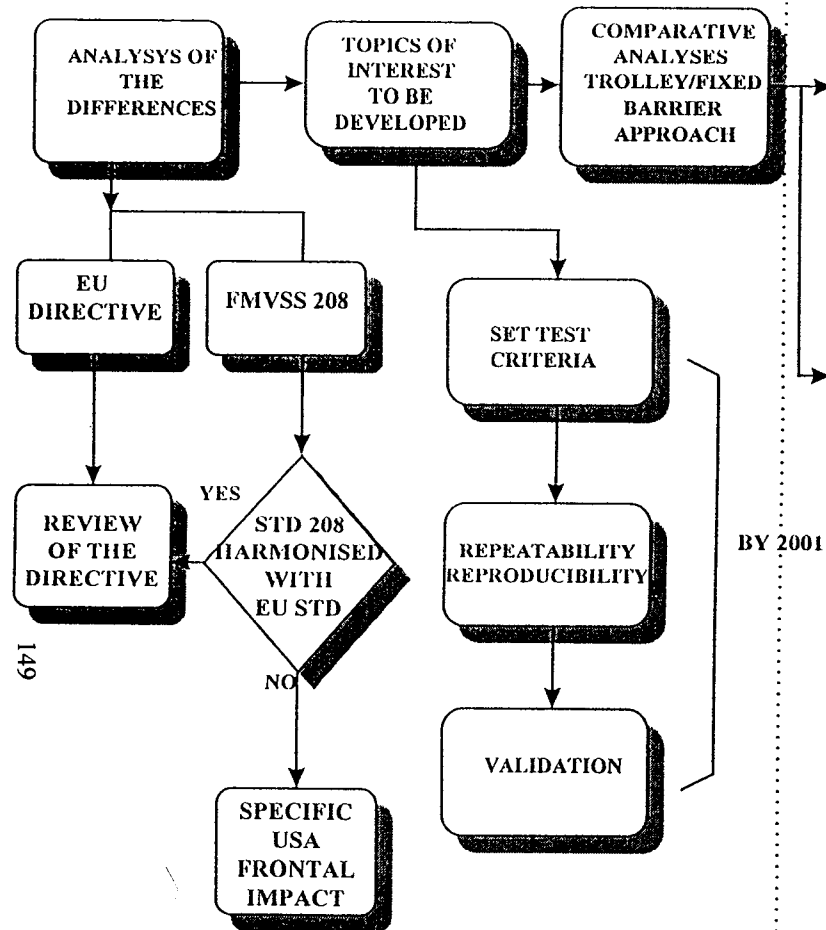
1. the potential benefits of using a mobile barrier
2. provide indications of possible modifications to the present EU test procedure based on the European accident studies.

## **2.2 Schedule time**

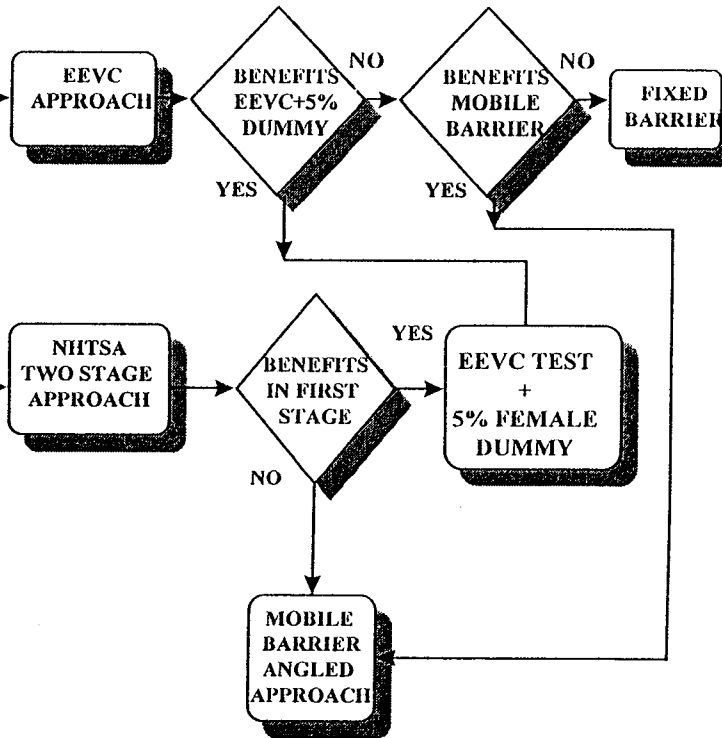
The group has not yet resumed the deadlines of this second stage because premature.



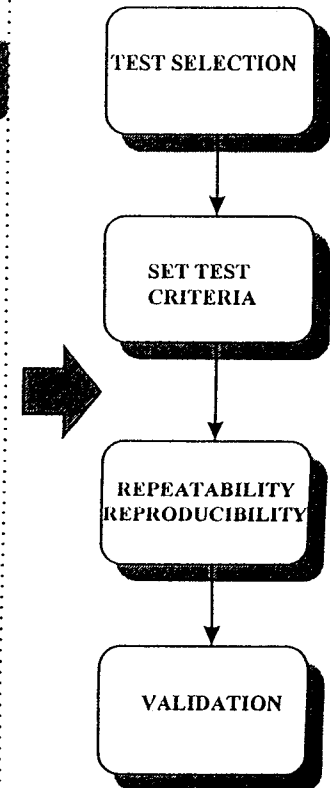
## PROBLEM DEFINITION



## FIND KEY CHARACTERISTICS



## TEST METHOD



# FRONTAL OFFSET CRASH TEST STUDY USING 50TH PERCENTILE MALE AND 5TH PERCENTILE FEMALE DUMMIES

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Paper Number 98-S1-O-01

## ABSTRACT

In September of 1996, United States Congress directed the National Highway Traffic Safety Administration (NHTSA) to conduct a feasibility study toward establishing a Federal Motor Vehicle Safety Standard (FMVSS) for frontal offset crash testing. Congress stated that these activities should reflect ongoing efforts to enhance international harmonization of safety standards. The offset crash test work described herein is part of NHTSA's undertaking in response to the Congressional directive. This paper presents NHTSA's initial results of offset testing where the test vehicle moves at a speed of 60 kmph into a fixed deformable barrier that overlaps 40 percent of the front of the vehicle. This test procedure essentially replicates that required by the European Union's (EU) Directive 96/79 EC, "On the Protection of Occupants of Motor Vehicles in the Event of a Frontal Impact and Amending Directive 70/156/EEC," which was adopted in December of 1996.

Previous testing with this particular frontal offset procedure has suggested that the lower legs of the dummies show loads that exceed possible injury limits. One goal of this testing activity is to determine if the offset test at 60 kmph provides additional benefits beyond the FMVSS No. 208 full frontal barrier test at 48 kmph. In addition, the agency has been petitioned to use smaller size dummies in its testing to look for aspects of safety that are not evaluated by the traditional 50<sup>th</sup> percentile male Hybrid III dummy.

To facilitate the potential for adding the 5th percentile to frontal testing and to evaluate the offset test with the 50<sup>th</sup> and 5<sup>th</sup> percentile dummies, a series of eight crash tests was performed. In the eight crash tests, all the dummies were restrained with the safety belt systems. The three cars used in the crash testing were the Dodge Neon, Toyota Camry, and Ford Taurus.

## Background

Safety experts have noted that lower extremity trauma is strongly associated with disability. Luchter found that — in police reported tow away motor vehicles crashes in the USA — lower extremity injuries resulted in 41 percent of life-years lost to injury and 17 percent of total societal costs. [1] Miller et al. estimated that lower limb injuries are the second largest component of nonfatal highway crash costs. They determined that, for drivers and right front seat passengers in frontal collisions with no rollover or ejection, lower limb injuries cost \$8.2 billion per year. [2]

Pletchen et al. studied the trauma of 143 belted drivers of Mercedes-Benz passenger cars and found that the trauma of the lower extremities was ranked second highest in injury costs. [3] Morgan et al. examined the 1979 - 1986 National Automotive Sampling System (NASS) file for frontal crashes and determined that lower extremity trauma covers about 26 percent of the total moderate or greater injuries (AIS  $\geq 2$  count) for both belted and unbelted occupants. [4] Stucki et al. studied the NASS crash data files for the years 1988 - 1993 and again found that, in frontal crashes, approximately 25 percent of AIS  $\geq 2$  injuries are to the lower extremities. [5]

Grosch et al., of Daimler-Benz, studied passenger car intrusion in frontal crashes. For a passenger car to withstand vehicle intrusion, they believed that a passenger compartment must be sufficiently stiff. They suggested that, to minimize injury related to vehicle intrusion, it is essential to conduct appropriate crash tests such as offset collisions with an overlap of less than 40%. [6] Planath-Skogsmo et al., of Volvo, studied the differences in various types of frontal crash tests. From their study, they found that to assess the vehicle structural properties, either a severe partial overlap collision or Offset Deformable Barrier (ODB) tests can be used to complement the existing full frontal barrier test. [7] Also, in the United Kingdom, the Transport and Road Research laboratory conducted an investigation based on real world crashes. They indicated that, despite the use of seat belts, frontal impacts pose the greatest threat to car occupants due to vehicle intrusion. In

that study, they suggested that there is a need for a test in which the barrier is offset and a deformable impact face is used. [8] In the U.S., beginning in 1995, the Insurance Institute for Highway Safety (IIHS) initiated a program using a frontal offset test to rate safety in cars. This ongoing frontal offset testing program evaluates the crashworthiness of new model vehicles crashed at 64 kmph (40 mph) into a deformable barrier. Based on their experience, they indicated that a full-width test and a frontal offset test complement each other; a full-width test is especially demanding of restraints, while the offset test is demanding of the structural integrity of a vehicle. [9]

In 1996, Australia studied the benefits of a frontal offset regulation. In their study, they found that adding the EEVC frontal offset requirement to the Australia's Federal Office of Road Safety (FORS) dynamic full frontal crash standard (ADR 69, similar to FMVSS No. 208), would be highly beneficial and cost effective. [10]

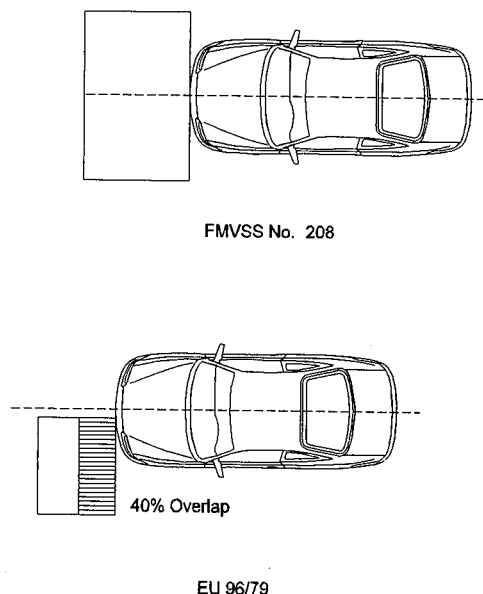
### NHTSA's Frontal Offset Harmonization Study

In September of 1996, Congress directed NHTSA to conduct a feasibility study toward establishing a Federal motor vehicle safety standard for frontal offset crash testing. In that directive, Congress stated, "...such a standard will enhance automobile safety for all consumers. Further, these activities should reflect ongoing efforts to enhance international harmonization of safety standards...." The offset test program described herein is part of NHTSA's undertaking to form standards that provide benefits and reflect efforts to strengthen world wide harmonization. [11]

In December of 1996, the European Parliament adopted Directive 96/79 EC, "On the Protection of Occupants of Motor Vehicles in the Event of a Frontal Impact and Amending Directive 70/156/EEC." Directive 96/79/EC requires a 40% frontal offset test of a vehicle into a deformable barrier at 56 kmph, with a restrained 50<sup>th</sup> percentile adult Hybrid III anthropomorphic dummy. Also, in Australia, the Federal Office of Road Safety (FORS) is considering adopting Australian Design Rule (ADR) 73/00 Offset Frontal Impact Occupant Protection, which is identical to the Directive 96/79 EC. Furthermore, in Japan, since April 1993, the Ministry of Transport (MOT) has been researching a frontal offset test procedure similar to Directive 96/79 EC.

In Figure 1, the configurations of the FMVSS No. 208 test and the European Parliament adopted Directive 96/79 EC frontal 40% offset test are shown. The test conditions

and injury criteria prescribed in the FMVSS No. 208 standard and the EU Directive 96/79/EC differ considerably. The differences are listed in Table A1 of Appendix A.



**Figure 1. Test configurations of FMVSS No. 208 and the EU-offset Deformable Barrier tests.**

In 1997, the Canadian Government carried out a test program to validate the 40% offset crash test procedure designated in the Directive 96/79 EC. Four separate passenger cars were crashed at the speed of 56 kmph and at a higher speed of 60 kmph. In that study, at the impact speed of 60 kmph, the lower leg readings exceeded the allowed tibia criteria of the EU (European Union) Directive three times out of eight. [12] Based on that study, the European Parliament and Australian FORS are considering increasing the impact speed to 60 kmph.

### 5<sup>th</sup> Percentile Female Hybrid III Dummy

In September of 1996, the American Automobile Manufacturers Association (AAMA) petitioned NHTSA to change the FMVSS No. 208 testing specifications. [13] Among other items, the petition requested the use of the 5th percentile adult female Hybrid III dummy in FMVSS No. 208. Subsequently, the NHTSA received a second petition to incorporate the 5th percentile female Hybrid III dummy into FMVSS No. 208. [14] The size of the occupant may be important in determining the safety value of different

frontal crash procedures. Previous research into frontal crash protection has suggested that trauma risk levels differ by occupant size. [5] The general description and relative seating configuration of various adult dummy sizes are included in Table A2 and Figure A1 of Appendix A.

To use the 5<sup>th</sup> percentile female Hybrid III dummy in vehicle testing, a common seating procedure needs to be established. In July of 1997, a special task force of the SAE Dummy Test Equipment Subcommittee met at East Liberty, Ohio, to draft a seating procedure for the 5<sup>th</sup> percentile adult female Hybrid III dummy to use in passenger cars. Representatives from Chrysler, Ford, General Motors (GM), IIHS, KARCO, NHTSA, Toyota, Transportation Research Center, Transport Canada, and the University of Michigan were present. Existing seating procedures were studied and all parties agreed on a procedure, which is being finalized by the SAE subcommittee.

With the development of the 5<sup>th</sup> percentile female dummy seating procedure, NHTSA began frontal offset testing. The objectives of this testing are to (1) evaluate potential benefits of adopting the frontal offset test as a supplement to FMVSS No. 208 and (2) to evaluate the use of the 5<sup>th</sup> percentile female dummy in both the FMVSS No. 208, restrained test condition and in the offset test condition.

### Crash Test Matrix

The agency crashed eight cars to understand the EU frontal offset and the response of the 5<sup>th</sup> percentile female dummy. Tests were conducted with three model year 1996 passenger cars — Dodge Neon, Toyota Camry, and Ford Taurus — using two dummies, the 50th percentile male Hybrid III dummy and the 5th percentile female Hybrid III dummy. The tests were conducted using all available restraints. The conditions of the eight tests are shown in Table 1.

Vehicle selection was based on choosing vehicles for which (1) frontal impact test data already exist, (2) there are a large number of these cars sold in the U.S., and (3) there is a sales presence of these cars throughout the world. Of the three vehicles chosen, the Dodge Neon was one of the passenger cars tested by Transport Canada.[12] The Ford Taurus and the Toyota Camry are two passenger cars that have been tested extensively by NHTSA and IIHS.

All testing used the full instrumentation package available for the Hybrid III dummies. In this study, one of the primary interests is evaluating the lower extremity. A

typical instrumented lower leg is configured with load cells at the upper and lower tibia with a 45 degree dorsiflexion angle foot with a rubber stopper. In this test series, the configurations of the instrumented legs used for the two dummy sizes are slightly different. The difference is that the 50<sup>th</sup> percentile male dummy configured with a single axis load cell (measures moments about the y-axis) whereas the 5<sup>th</sup> percentile female dummy configured with dual axes load cells (measures moments about x and y axes).

**Table 1.**  
**Test Matrix for the 1997 NHTSA's EU-offset**  
**feasibility study**

Frontal Test	Dodge Neon	Toyota Camry	Ford Taurus
Full @ 48 kph with 5th% female dummy	1	2	3
40% Offset @ 60 kph with 50th% male dummy, restrained	✓	4	5
40% offset @ 60 kmph with 5th% female dummy	6	7	8
✓ = data already exists for this test condition and make model combination [12]			

In each test of their car, engineers from Chrysler, Ford, and Toyota assisted the NHTSA with seating the 5th percentile female dummy. For most of the tests, the manufacturer's representatives actively participated in the test setup. All the test results have been compiled into reports, films and videos and are available through the NHTSA's public dockets (*Docket number*: NHTSA 98-3332).

### RESULTS AND DISCUSSION

All of the dummy responses from the tests are tabulated in Tables A3 and A4 of Appendix A, for the driver and right front passenger, respectively. In the following analyses, the difference dummy responses are compared in terms of values that have been normalized to the preliminary injury criteria and Injury Assessment Reference Values (IARV) that are given in Table A5 of Appendix A. As the notes in this table indicate, many of the reference values are preliminary and subject to change, particularly those associated with the 5<sup>th</sup> percentile female dummy.

## Head, Chest, and Femurs

In Figures 2, 3, and 4, the head and chest responses of the 5<sup>th</sup> percentile female Hybrid III are compared for the FMVSS No. 208 frontal test and the EU-offset test at 60 kmph. Note that the normalized responses are used in the figures. In general, the readings from the FMVSS No. 208 tests are either about the same or higher than those from EU-offset tests. Exceptions are that the chest displacement responses for the driver and right front passenger for the

Neon are considerably higher in the EU test.

The comparisons of the femur loads are shown in Figures 5 and 6. In the EU-offset test, the femoral loading is higher in the driver's left leg than in the right. For the passenger, the femoral loading is generally higher in the FMVSS No. 208 test. However, in each of five comparisons, none of the readings exceeded the allowable injury criteria. In fact, most of the readings are far below the allowable limit.

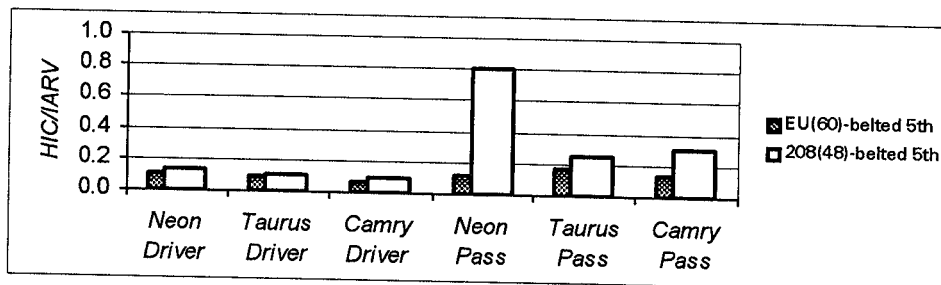


Figure 2. Head Injury Criterion (HIC) comparison.

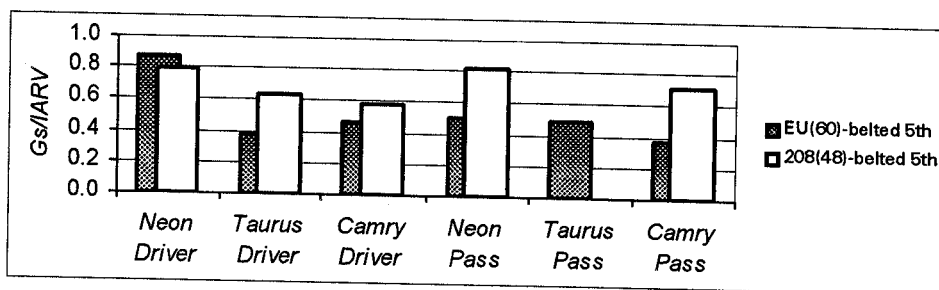


Figure 3. Chest acceleration (3ms clip) comparison

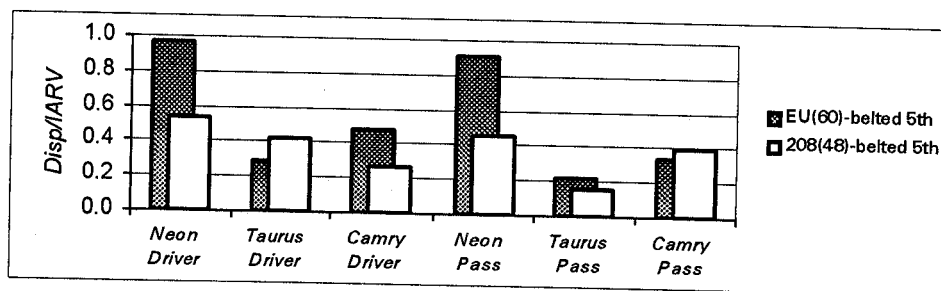


Figure 4. Chest displacement comparison

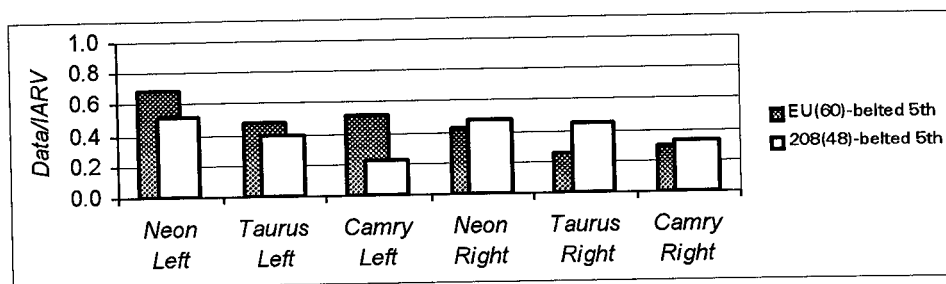


Figure 5. Driver femur comparison.

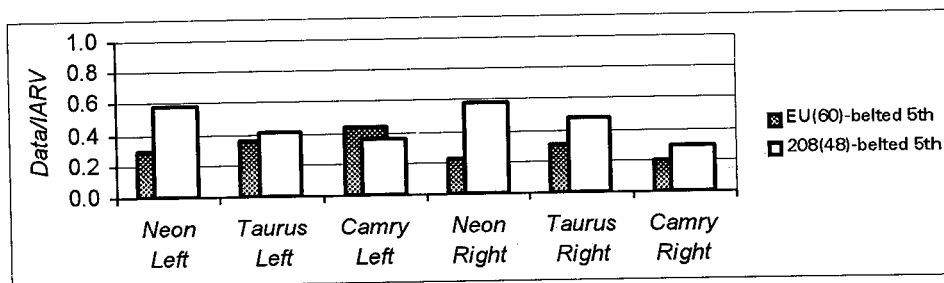


Figure 6. Right front passenger femur comparison.

## Lower Extremity

Does the EU-offset test demonstrate that the loads to the lower extremities are greater than those in the FMVSS No. 208 test? How do the lower extremity loads differ between the two dummy types — the 50<sup>th</sup> percentile male and the 5<sup>th</sup> percentile female? In this test series, the lower extremity data for the driver and right front passenger are collected for all tests. However, because of the benign responses exhibited from the right front passenger dummy in the offset tests, the following discussion will be limited to the driver dummy. The right front passenger dummy readings are in Table A4 of Appendix A for the interested readers.

Two types of lower limb analyses are made: a comparison between test types given both used the 5<sup>th</sup> percentile female dummy and a comparison of the 5<sup>th</sup> percentile female and the 50<sup>th</sup> percentile male dummies given both were exposed to EU-offset test conditions. For this lower extremity comparison, the injury criteria for the upper and lower tibia moments and foot/ankle axial loading forces are examined. For the tibia bending moment comparisons, resultant bending moments are used except for the lower leg data for the 50<sup>th</sup> percentile male dummy — only the bending moments about y-axis were available.

First, the lower limbs of the 5<sup>th</sup> percentile female dummy were examined between the two test types. In Figures 7 and 8, the comparisons of left and right legs are

shown. In the Taurus, all values are below the reference values and are similar for both test types.

In the Camry, all values except the lower tibia moment are below the reference values. The right lower tibia moment in the EU-offset test is considerably higher than that observed in the FMVSS No. 208 test. When the difference is calculated for the right lower tibia moment, the reading for the EU-offset test is greater by 103%.

In the Neon, higher tibia forces and moments occurred in both test types than for the Taurus and Camry. The axial force reference value is exceeded in the FMVSS No. 208 test and the upper and lower tibia moment reference values are exceeded in both test types. Of the four tibia moment comparisons for the Neon, between the two test types, the readings of the 5<sup>th</sup> percentile female exceed the allowable criteria in six out of the eight responses. When the percent difference is calculated between the two test types, the readings for the EU-offset test for Neon at the left and right lower tibia bending moments are higher by 137% and 101%, respectively. By contrast, the left upper tibia moment for the Neon in the FMVSS No. 208 test exceeds the response from the EU test by 75%.

Second, does the 5<sup>th</sup> percentile female dummy exhibit any difference in loadings to the lower limbs as compared to the 50<sup>th</sup> percentile male dummy under the EU-offset test condition? The lower limb comparisons between the 5<sup>th</sup>

percentile female and the 50<sup>th</sup> percentile male dummies for the EU-offset tests are shown in Figures 9 and 10. For the Taurus, little difference is noted between the responses of

the two dummy types with all responses meeting the reference values.

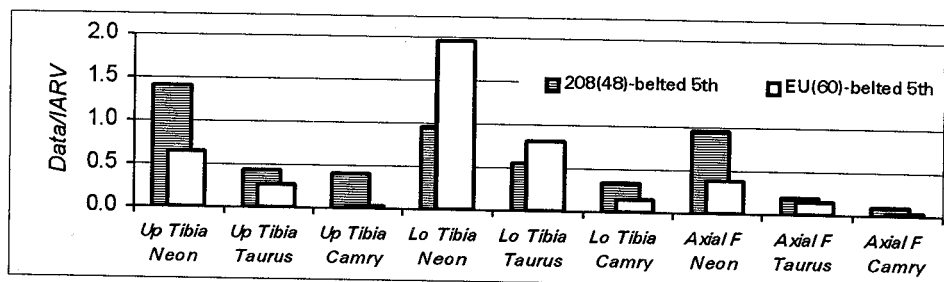


Figure 7. Driver left leg tibia comparison of the 5th percentile female dummy between the EU-offset and the FMVSS No. 208 tests.

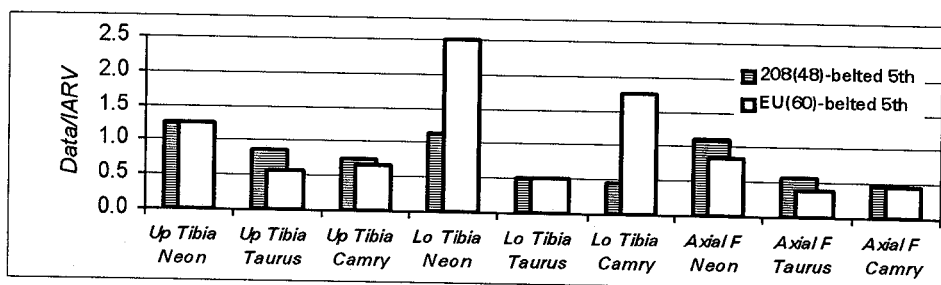


Figure 8. Driver right leg tibia comparison of the 5th percentile female dummy between the EU-offset and the FMVSS No. 208 tests.

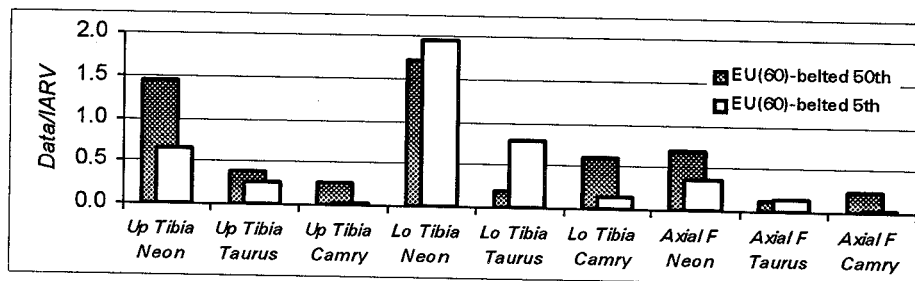


Figure 9. Driver left leg tibia comparison between the two dummy types in the EU-offset test.

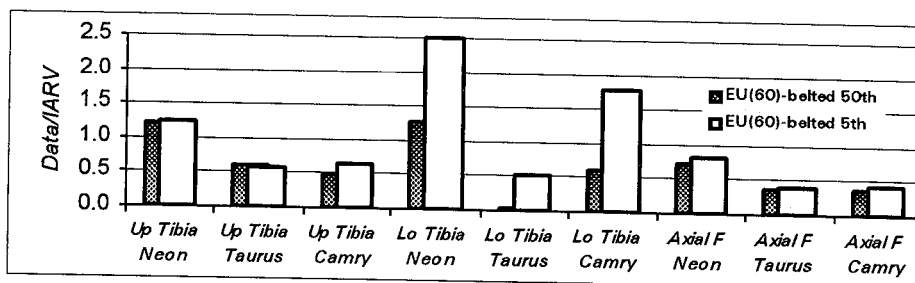


Figure 10. Driver right leg tibia comparison between the two dummy types in the EU-offset test.

For the Camry, again, most responses are similar for the two dummies except for the right lower tibia moment. When the difference is calculated, at the right lower tibia for Camry, the reading for the 5<sup>th</sup> percentile dummy is greater by 115% than for the 50<sup>th</sup> percentile male dummy. The reading for the 5<sup>th</sup> percentile female exceeds the reference value whereas the 50<sup>th</sup> percentile male does not.

For the Neon, the right tibia moment of the 5<sup>th</sup> percentile female is greater by 124% than the 50<sup>th</sup> percentile male dummy — both readings exceed the reference value. By contrast, for the left upper tibia moment, the reading of the 50<sup>th</sup> percentile male dummy is greater by 80%.

In general, the comparisons in Figures 7 and 8 suggest that the higher dummy readings above the preliminary reference values for lower tibia bending moment are exhibited in the EU-offset test than the FMVSS No. 208 test. In addition, the comparisons in Figures 9 and 10 suggest that when the readings for the two dummies are compared for the EU-offset test, the result shows that the 5<sup>th</sup> percentile generally shows greater loads in the lower limbs than the 50<sup>th</sup> percentile male dummy in the EU-offset test.

As discussed in the foregoing analysis, greater lower limb readings may be expected from the EU-offset test. It is also found, as expected, that generally greater intrusion occurs in the EU tests than in the FMVSS No. 208 tests. In Table A6 of Appendix A, the intrusion measurements of toepan collected from the test series are tabulated. From these intrusion data, it is noted that the Neon, which exhibited the higher lower leg responses, had the most intrusion (about twice as much as the other two vehicles).

## Neck Response

Because of its different anthropometric properties, the small female may be exposed to different injury risks in frontal crashes than the mid-size male. In the previous sections, risks to the legs were explored. In this section, the potential for neck injury will be examined. For the neck evaluation, five injury criteria are examined: fore-and-aft shear, axial compression, axial tension, bending in flexion, and bending in extension. In reviewing the dummy readings, the outcome reveals that no significant neck readings are found for the criteria of shear, compression, tension or flexion. However, the neck extension readings are consistently high (exceed the preliminary reference neck extension criterion of 31 Nm found in Table A5) in the neck of the 5<sup>th</sup> percentile female

dummy.

To further evaluate the neck extension criterion, two types of analyses are made: the comparison of the 5<sup>th</sup> percentile female and the 50<sup>th</sup> percentile male dummies in EU-offset test conditions and the 5<sup>th</sup> percentile female dummy comparison between the test types. In each comparison, the neck responses for both driver and right front passenger are included.

First, the driver neck extensions for the two dummies tested under EU-offset test are compared and shown in Figure 11. For the 5<sup>th</sup> percentile female dummy, all readings exceed the allowable limit by 1.61, 1.23, and 1.57 times for Neon, Taurus, and Camry, respectively. Whereas, for the 50<sup>th</sup> percentile male dummy, the reading for Camry exceeds the preliminary reference neck extension criterion of 31 Nm, a pertinent neck criterion by 1.1 times.

Figure 12 shows the neck extension comparison for the right front passenger between the two dummy types tested for EU-offset. In that comparison, the 5<sup>th</sup> percentile female dummy for Camry exhibits neck loading that exceeds the preliminary reference value by 2.9 times (89 Nm). In this particular event, the maximum neck extension occurred at 85 msec. Based on the high speed film analysis, the dummy's neck is being hyper-extended corresponding to the time that the neck load cells reads this maximum value.

Second, the neck extension readings for the driver 5<sup>th</sup> percentile female dummy are compared between the two test types and the comparison is shown in Figure 13. Between the two test types, the readings exceed the preliminary reference value five times out of six. Of the five high responses, the two highest readings are from the FMVSS No. 208 test for Taurus and Camry where the readings exceed the preliminary reference value by 2.4 and 2.1 times, respectively. Moreover, when the difference in readings is calculated, the readings for the FMVSS No. 208 are greater by 116% and 49% for Taurus and Camry, respectively. For the right front passenger dummy, Figure 14 shows neck extension comparison between the two test types. As can be seen, neither the Neon nor Taurus exceeds the preliminary reference value. However, the reading of the FMVSS No. 208 test for the Camry exhibits 5.6 times the preliminary reference value (172 Nm). When the difference is calculated, the reading for the FMVSS No. 208 test is greater by 270% than the EU-offset test. When the high speed film analysis is made, it shows that the dummy's neck is being hyper-extended at 73 msec.



Therefore, based on the neck analysis, between the driver and right front passenger, the readings for the driver 5<sup>th</sup> percentile female dummy exceed the preliminary reference value four times out of six. In addition, when the neck extension for the 5<sup>th</sup> percentile female dummy is

compared between the two test types, for both driver and right front passenger dummies, the readings from the FMVSS No. 208 test are higher than those from the EU-offset test.

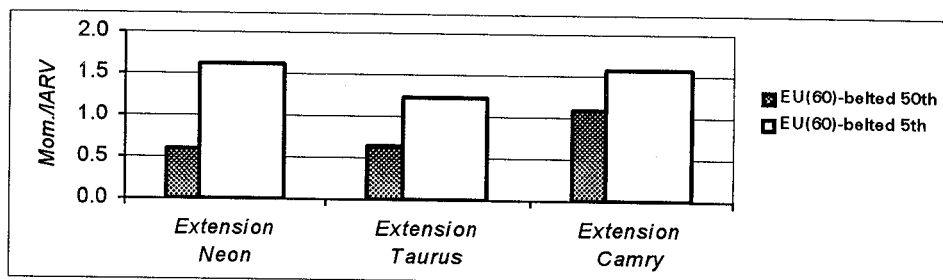


Figure 11. Driver neck bending moment comparison between the two dummy types in EU-offset test.

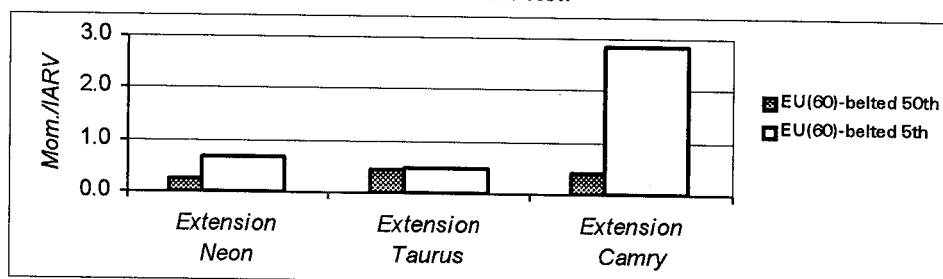


Figure 12. Passenger neck bending moment comparison between the two dummy types in EU-offset test.

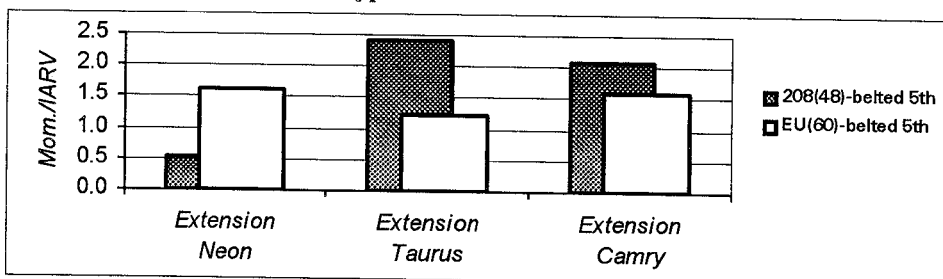


Figure 13. Driver neck bending moment comparison of the 5<sup>th</sup> percentile female Hybrid III between the two test types.

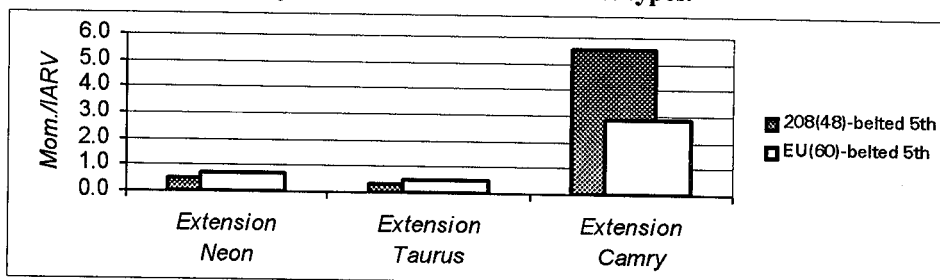


Figure 14. Right front passenger neck bending moment comparison of the 5<sup>th</sup> percentile female Hybrid III between the two test types.

## CONCLUSIONS

The U.S. Congress directed NHTSA to investigate a frontal offset test procedure required by the EU Directive 96/79 EC. The NHTSA also took this opportunity to investigate the potential for adding the 5<sup>th</sup> percentile female dummy to a frontal flat barrier test and a frontal offset test. A series of eight crash tests was performed. In these tests, all dummies were restrained. The three cars used in the testing were the Dodge Neon, Ford Taurus, and Toyota Camry.

When the results for the 5<sup>th</sup> percentile female dummy are compared between the belted EU-offset test and the belted FMVSS No. 208 test, it is found that the responses for head, chest and femur from the FMVSS No. 208 test are about the same or slightly greater. By contrast, for the lower limb and neck criteria, considerable differences are found.

First, in the lower limb comparisons, when the readings are compared between the FMVSS No. 208 and EU-offset tests, the result suggests that the higher readings are exhibited more in the EU-offset test. For instance, in two occasions, the tibia readings for the EU-offset test exceed the preliminary reference values considerably whereas for the FMVSS No. 208 test these criteria are satisfied. In addition, when the lower limb readings for the two dummy sizes are compared in the EU-offset test, the results show that the 5<sup>th</sup> percentile female exhibits considerably greater loads than the 50<sup>th</sup> percentile male. In that comparison, in one occasion, the 5<sup>th</sup> percentile female dummy exceeds the preliminary reference values whereas the 50<sup>th</sup> percentile male does not.

Therefore, the result suggests that for the 5<sup>th</sup> percentile female dummy, the EU-offset test provides an additional benefit in assessing trauma in the lower limbs beyond that of the FMVSS No. 208 test. Furthermore, it reveals that in the EU-offset test condition, the 5<sup>th</sup> percentile female dummy would likely produce higher lower limb readings than the 50<sup>th</sup> percentile male dummy.

Second, the neck criteria for the 5<sup>th</sup> percentile female and the 50<sup>th</sup> percentile male dummies are evaluated. The results show that all of the neck criteria are satisfied except for the neck extension criterion. When the neck extension readings for the 5<sup>th</sup> percentile female are compared to the 50<sup>th</sup> percentile male dummy for the EU-offset test, between the driver and right front passenger dummies, the 5<sup>th</sup> percentile female exceeds the preliminary reference values four times by factors of 1.61, 1.23, 1.57 and 2.9 — none of

the 50<sup>th</sup> percentile male dummy responses exceeds the preliminary reference values.

Furthermore, when the readings for the 5<sup>th</sup> percentile female are compared, between the two test types, the driver 5<sup>th</sup> percentile female dummy exceeds the preliminary reference values five times out of six by factors of 1.23 to 2.39. In addition, for the right front passenger, between the two test types, the 5<sup>th</sup> percentile female dummy exceeds the preliminary reference values two times out of six, by factors of 2.9 and 5.6. Of the seven highest neck readings mentioned, the three highest readings are exhibited from the FMVSS No. 208 test using the smaller dummy.

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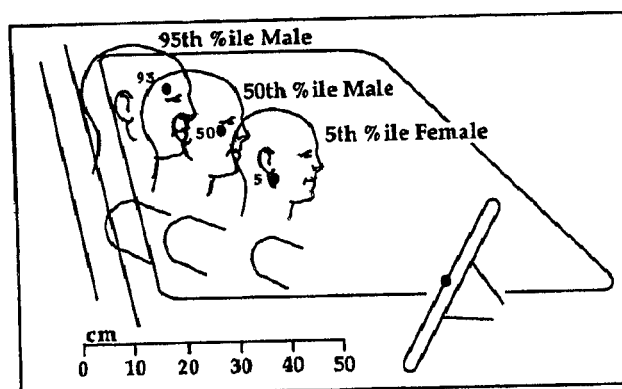
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## Appendix A.

**Table A1.**  
**General summary of the test requirements for the FMVSS No. 208 and EU Directive 96/79/EC used for this study.**

	FMVSS No. 208	EU Directive 96/79/EC
Impact Speed	48 kmph (30 mph)	56 kmph (35 mph)
Impact Object	fixed rigid barrier	fixed deformable barrier
Vehicle Frontal Overlap With Barrier	full frontal	40% overlap of the vehicle width directly in line with the barrier face
Dummy Type and Conditions	belt restrained 50 <sup>th</sup> percentile Hybrid III male	belt restrained, 50 percentile Hybrid III male
Injury Criteria	includes threshold criteria for the head, chest deceleration, chest deflection, femur, and neck (only under the optional sled test)	includes the same threshold criteria, and in addition, viscous criteria (V*C), the neck, the knee, tibia index (inner lower leg), foot/ankle compression and compartmental intrusion



**Figure A1. Relative driver dummy sitting position**  
( Parkin, S., Mackay, G. M., and Cooper, A., "How Drivers Sit in Cars,"  
Accident Analysis & Prevention, Institute of Transportation Studies,  
University of California, Irvine, Pergamon Press, Vol.27, No. 6, December 1995.)

**Table A2.**  
**Hybrid III dummy weights and heights**  
**For detail information, refer to reference No. 17**

Dummy Type	Standing Height (cm)	Sitting Height (cm)	Weight (kg)
5 <sup>th</sup> % Female Hybrid III	149.9	78.7	49.3
50 <sup>th</sup> % Male Hybrid III	174.5	88.4	77.8

**Table A3.**  
**Dummy readings for driver. These results are from the offset test series**  
**except for the Neon EU-offset test data for 50<sup>th</sup> percentile male (from Transport Canada)**

HIC, Chest 3ms Clip, & Chest Displacement - Driver Side									
	HIC			Chest 3ms clip (G)			Chest Displacement (mm)		
	Neon	Taurus	Camry	Neon	Taurus	Camry	Neon	Taurus	Camry
EU(60)-belted 50th	583.0	343.0	407.0	40.0	30.0	33.7	30.0	29.5	21.5
EU(60)-belted 5th	111.5	86.0	70.5	52.4	23.0	28.0	50.8	16.0	25.3
208(48)-belted 5th	137.0	104.0	96.2	47.0	38.0	34.8	29.0	22.2	13.8
Neck Force - Driver Side									
	Shear (N)			Compression (N)			Tension (N)		
	Neon	Taurus	Camry	Neon	Taurus	Camry	Neon	Taurus	Camry
EU(60)-belted 50th	167.5	732.1	549.5	777.6	611.0	1589.3	1974.1	1445.2	1037.9
EU(60)-belted 5th	546.0	455.0	733.0	283.0	109.0	108.0	1532.0	1783.0	1228.0
208(48)-belted 5th	301.0	1054.0	1093.4	456.0	547.0	414.0	1757.0	2389.0	2254.9
Neck Bending Moment - Driver Side									
	Flexion (Nm)			Extension (Nm)					
	Neon	Taurus	Camry	Neon	Taurus	Camry			
EU(60)-belted 50th	37.0	36.0	23.3	33.6	36.9	62.8			
EU(60)-belted 5th	12.0	5.0	6.1	50.0	38.0	48.7			
208(48)-belted 5th	17.0	6.0	12.9	16.0	74.0	63.8			
Lower Extremity in Left Leg - Driver Side									
	Upper Tibia Bending (Nm)			Lower Tibia Bending (Nm)			Axial Force (N)		
	Neon	Taurus	Camry	Neon	Taurus	Camry	Neon	Taurus	Camry
EU(60)-belted 50th	326.6	88.2	57.1	383.4	41.2	138.0	5667.7	962.0	1915.9
EU(60)-belted 5th	74.5	31.4	3.8	224.8	92.4	17.1	1891.0	731.0	97.8
208(48)-belted 5th	161.2	48.8	46.0	108.9	63.8	39.4	4875.0	1023.0	492.4
Lower Extremity in Right Leg - Driver Side									
	Upper Tibia Bending (Nm)			Lower Tibia Bending (Nm)			Axial Force (N)		
	Neon	Taurus	Camry	Neon	Taurus	Camry	Neon	Taurus	Camry
EU(60)-belted 50th	272.6	138.5	111.7	282.1	8.6	138.1	5868.1	2810.0	2781.0
EU(60)-belted 5th	143.0	64.9	74.5	286.4	58.4	202.8	4201.0	1967.0	2210.0
208(48)-belted 5th	143.4	99.6	86.0	129.5	58.1	52.4	5602.0	2894.0	2439.7
Femur Force -Driver Side									
	Left Leg (N)			Right Leg (N)					
	Neon	Taurus	Camry	Neon	Taurus	Camry			
EU(60)-belted 50th	6896.9	2577.0	2276.0	4902.1	3493.0	2958.0			
EU(60)-belted 5th	4273.0	2928.0	3147.0	2571.0	1535.0	1830.0			
208(48)-belted 5th	3161.0	2453.0	1344.5	2963.0	2729.0	2011.8			

Table A4.

Dummy readings for right front passenger. These results are from the offset test series except for the Neon EU-offset test for the 50<sup>th</sup> percentile male (from Transport Canada)

HIC, Chest 3ms Clip, & Chest Displacement - Right Front Side									
	HIC			Chest 3ms clip (G)			Chest Displacement (mm)		
	Neon	Taurus	Camry	Neon	Taurus	Camry	Neon	Taurus	Camry
EU(60)-belted 50th	246.0	252.0	236.0		31.7	29.3	21.9	30.0	31.5
EU(60)-belted 5th	116.0	165.0	130.6	29.7	29.0	22.0	48.8	11.1	17.9
208(48)-belted 5th	806.0	255.0	303.0	49.0		42.5	24.0	8.4	20.6
Neck Force - Right Front Side									
	Shear (N)			Compression (N)			Tension (N)		
	Neon	Taurus	Camry	Neon	Taurus	Camry	Neon	Taurus	Camry
EU(60)-belted 50th	675.1	470.1	499.5	361.8	130.3	245.6	1086.0	928.8	1086.0
EU(60)-belted 5th	694.0	1063.0	1385.0	208.0	1667.0	239.0	719.0	658.0	1579.0
208(48)-belted 5th	503.0	1284.0	2907.9	304.0	869.0	154.6	1437.0	988.0	1993.1
Neck Bending Moment - Right Front Side									
	Flexion (Nm)			Extension (Nm)					
	Neon	Taurus	Camry	Neon	Taurus	Camry			
EU(60)-belted 50th	38.1	30.7	32.0	14.4	25.8	22.3			
EU(60)-belted 5th	48.0	93.0	22.7	21.0	15.0	88.7			
208(48)-belted 5th	29.0	104.0	15.7	15.0	9.0	172.3			
Lower Extremity in Left Leg - Right Front Side									
	Upper Tibia Bending (Nm)			Lower Tibia Bending (Nm)			Axial Force (N)		
	Neon	Taurus	Camry	Neon	Taurus	Camry	Neon	Taurus	Camry
EU(60)-belted 50th									
EU(60)-belted 5th	60.4	105.0	43.9	19.8		14.8	1157.0	1744.0	1639.0
208(48)-belted 5th	106.8	42.7	48.1	51.7	37.0	22.0	3067.0	2332.0	3525.0
Lower Extremity in Right Leg - Right Front Side									
	Upper Tibia Bending (Nm)			Lower Tibia Bending (Nm)			Axial Force (N)		
	Neon	Taurus	Camry	Neon	Taurus	Camry	Neon	Taurus	Camry
EU(60)-belted 50th									
EU(60)-belted 5th	60.9	35.5	24.0	0.6	0.4	0.4	42.0	26.0	26.0
208(48)-belted 5th	89.6	47.3	57.0		0.3			44.0	
Femur Force - Right Front Side									
	Left Leg (N)			Right Leg (N)					
	Neon	Taurus	Camry	Neon	Taurus	Camry			
EU(60)-belted 50th		3728.0	2806.0		1993.0	834.0			
EU(60)-belted 5th	1830.0	2238.0	2715.0	1344.0	1857.0	1253.0			
208(48)-belted 5th	3605.0	2527.0	2218.1	3620.0	2944.0	1813.3			

**Table A5.**  
**Preliminary Injury Assessment Reference Values. These values are currently being reviewed by the agency and are subject to change**

Dummy/Body Region	Hybrid III 5%	Hybrid III 50%
Head-HIC (36ms)	1000	1000 (2)
Neck Flexion Bend. Mom. - Nm	104 (1)	190 (1)(2)
Neck Extens. Bend. Mom. -Nm	31 (1)	57 (1)(2)
Neck Axial Tension - N	2201-8.6*(T1-T2); 1934-52.2*(T1-T2) for $\Delta T > 31\text{ms}$ (1)	3300-11.4*(T1-T2); 2900-72*(T1-T2) for $\Delta T > 35\text{ms}$ (1)
Neck Axial Compression - N	2668-71.6*(T1-T2); 734 for $\Delta T > 27\text{ms}$ (1)	4000-96.7*(T1-T2) 1100 for $\Delta T > 30\text{ms}$ (1)
Neck Fore-and-Aft Shear - N	2068-53.4*(T1-T2) 1000 for $\Delta T$ 20-29ms 734 $\Rightarrow \Delta T > 37\text{ms}$ (1)	3100-64*(T1-T2) 1500 for $\Delta T$ 25-35ms 1100 $\Rightarrow > 45\text{ms}$ (1)
Chest Acceleration - G (3ms cut-off)	60	60 (2)
Chest Deflection - mm	53 (1)	65 (1)
Femur - Axial Compr - N	6186	10,000(2)
Ankle/foot - Axial Compr. - N	5104	8000
Mc-Crit. Bend Mom.- Nm	115	225

(1) "Anthropomorphic Dummies for Crash and Escape Systems", AGARD Conf. Proceedings, July 1996, AGARD-AR-330,  
(2) FMVSS No. 208

**Table A6.**  
**Intrusion of upper (Level 1) and lower (Level 2) toeboard.**  
**These are based on pre and post test measurement done by hand**

		40 % Offset 60 kph <sup>1</sup>		FMVSS 208 48 kph				40 % Offset 60 kph <sup>1</sup>		FMVSS 208 48 kph	
		Level 1 (mm)	Level 2 (mm)	Level 1 (mm)	Level 2 (mm)			Level 1 (mm)	Level 2 (mm)	Level 1 (mm)	Level 2 (mm)
Camry 1	Left	135	40	30	0	Camry 2	Left	145	75		
	Center	125	40	50	10		Center	165	100		
	Right	85	40	0	0		Right	160	65		
Taurus 1	Left	150	120	35	20	Taurus 2	Left	70	25		
	Center	145	135	37	20		Center	75	22		
	Right	130	100	40	22		Right	0	20		
Neon 1	Left	180	60	120	0	Neon 2	Left	296	219		
	Center	175	50	110	0		Center	282	215		
	Right	0	0	50	10		Right	212	148		

# DETERMINATION OF FRONTAL OFFSET TEST CONDITIONS BASED ON CRASH DATA

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## ABSTRACT

This paper reports on the test procedure development phase of the agency's Improved Frontal Protection research program. It is anticipated that even after all cars and light trucks have air bags for drivers and front seat passengers there will remain over 8,000 fatalities a year and over 100,000 moderate to severe injuries. This research program will address these injuries/fatalities through development of crash tests with impact conditions not currently addressed by FMVSS No. 208, development of additional or more appropriate instrumentation and injury criteria on the test surrogate, and evaluation of other sizes of test surrogates.

An analysis of crash data is presented using the National Automotive Sampling System (NASS) and the Fatality Analysis Reporting System (FARS) for fatality counts. The population is drivers in frontal collisions with air bag restraints. Using NASS, frontal impact modes are grouped into general "test" conditions which will best represent the real world impact environment. These general test conditions include full barrier, left and right offset, and other impact modes. Using these general groupings of impact conditions, the analysis further assesses degree of overlap and impact direction to determine more specifically which crash conditions result in highest injury/fatality to drivers with air bags. Injury/fatality risk is also assessed by driver size and body region, with a more detailed analysis of leg injuries. Finally, a preliminary benefits analysis is presented for a future frontal, left, offset test procedure.

A test procedure has been developed, and is reported on in a separate paper [1]. Collinear and oblique, offset, frontal crash testing, at different widths of overlap, has been conducted with several current model, "target" cars into a standard "bullet" car at closing speeds of about 110 kph. Dummy injury measurements and structural responses provide a basis for determining which impact conditions produce the most severe environment for

occupants with air bags. It appears that the oblique impact with over 50 percent overlap produces the most severe responses on the "target" car. Development of this impact configuration into a potential frontal test procedure has been completed using a moving deformable barrier (MDB).

## INTRODUCTION

In the United States, air bags with lap and shoulder belts are specifically required by legislation (i.e., the National Highway Traffic Safety Administration Authorization Act of 1991) for both front outboard seating positions in all passenger cars manufactured after September 1, 1997. They are also required in all light trucks, multipurpose passenger vehicles (e.g., vans, utility and sport vehicles), and buses with a gross vehicle weight rating of 3,846 kilograms (8,500 pounds) or less and an unloaded vehicle weight of 2,489 kilograms (5,500 pounds) or less manufactured after September 1, 1998. NHTSA's "Third Report to Congress - Effectiveness of Occupant Restraint Systems and Their Use", dated December 1996, estimates that drivers protected by air bags experience a reduced fatality risk of 11 percent overall and 31 percent in pure frontal accidents.

The detailed performance requirements for these systems are contained in Federal Motor Vehicle Safety Standard (FMVSS) No. 208, Occupant Crash Protection. The standard has long specified a barrier test requirement using both belted and unbelted dummies. Beginning in March, 1997, Standard 208 has been temporarily modified to allow for a 48 kmph sled test requirement for unbelted dummies which made it easier for manufacturers to quickly introduce less aggressive, depowered air bags. This temporary option expires in September, 2001 and thereafter the full barrier test is again required. The main dynamic performance requirements in FMVSS No. 208, either sled or barrier test, involves successful testing with a 50th percentile



adult dummy at all speeds up to 48 kilometers per hour (30 miles per hour) at all angles between perpendicular and 30 degrees to either side of perpendicular. The tests can be run both with the dummy being unbelted and with the belts on. "Successful" crash testing requires that the dummy Head Injury Criterion (HIC) be 1,000 or less, the dummy chest deceleration be 60 G's or less, and the dummy femur loads be at or below 10,000 Newtons. The chest deflection on the Hybrid III dummy must be less than 75 millimeters.

The agency is currently in the process of proposing further requirements for reducing air bag aggressiveness which will lead to advanced air bags. Based on assessment of technologies which will come available in the next few years future air bag systems may include variable level deployments, or suppression, based on crash severity, and/or restraint use, pre-crash occupant position and/or size. As previously noted the full barrier test will again be required in September, 2001 to possibly "recapture" injuries/fatality savings in high severity crashes which may have been lost with depowered air bags. Part of the analysis in this paper is to look at crashes which may be represented by the 30 mph fixed barrier test of FMVSS No. 208 in terms of frequency of involvement, and injuries.

Even after full implementation of driver and passenger air bags as required by FMVSS No. 208, it has been estimated that frontal impacts will still account for over 8,000 fatalities and 120,000 moderate-to-critical injuries (i.e., injuries of AIS  $\geq$  2). The fatality estimate is based on 1995 FARS figures adjusted to a baseline non-air bag fleet and applying an air bag effectiveness estimate of 11 percent (from the Agency's "Third Report to Congress - Effectiveness of Occupant Protection Systems and Their Use.") to predict fatalities for an all air bag fleet. The number of fatalities in non-rollover frontal impacts is based on the proportion estimated by the NASS analysis and the computations are shown as part of Table 9. The estimates of annual numbers of moderate-to-critical injuries are from the Agency's "Final Regulatory Evaluation - Actions to Reduce the Adverse Effects of Air Bags - FMVSS No. 208 - Depowering." The objective of this research program is to address these fatalities and injuries and provide a basis for the possible future improvements in frontal protection. This may include upgrade of FMVSS No. 208 injury criteria and test devices, and the development of supplementary test procedures for the evaluation of occupant injury in crashes of higher severity and in different impact modes than those

addressed by the current FMVSS No. 208 [2-5].

The agency has been directed by Congress to develop a frontal, offset compliance test to complement the current FMVSS No. 208 full frontal test. The agency is evaluating a 40 percent overlap, 60 Kmph full-fixed-deformable barrier test which has been adopted in Europe, but at a test speed of 56 kmph. This will determine whether benefits can be realized in the U.S. from adopting this test procedure in the near future. The plan for making this assessment was presented in a report to Congress in April, 1997. The results of the FY 1997 testing is presented in a proposed paper for the 16<sup>th</sup> ESV Conference [6]. The oblique/offset test being developed by NHTSA's Research and Development office would be considered a longer term project.

Defining the problem includes assessing crash data and identifying general laboratory test conditions that can be used to replicate the safety performance of air bag vehicles in use. Then, evaluating the performance of a variety of production vehicles under those preliminary crash conditions, comparing their performance, and conducting potential benefits assessments to guide the agency for the "final" selection of a test procedure(s).

Some general conclusions from the analysis are:

- For drivers in frontal collisions with air bags, the offset crash configurations with highest frequency and risk of serious to fatal injuries is a left offset, vehicle-to-vehicle impact with substantial overlap.
- Drivers with air bags have a higher risk of leg injury in left offset crashes than in other frontal crashes and, thus, reducing leg injuries should be a prime objective in development of a offset test procedure. Leg injury should address tibia, knee and ankle measures, not addressed currently in the standard.
- For left offset impacts, improvements to reduce injury should address leg/instrument panel and floor interaction and all regions with left side surfaces.
- The size grouping representing 50th percentile males results in the highest crash exposure and number of injuries/fatalities for left offset impacts. However, both smaller and larger drivers have a higher risk of AIS  $\geq$  2 injuries and larger drivers have higher risk of AIS  $\geq$  3 injuries and fatalities even though their crash exposure is much lower than that for the 50th percentile grouping.

- Based on various assumptions, a requirement for a left offset test procedure could save as many as 5,100 AIS $\geq$ 3 injuries and over 20,000 AIS $\geq$ 2 injuries each year. Leg injuries alone could be reduced annually by about 11,000 for AIS $\geq$ 2 and about 2,000 for AIS $\geq$ 3. Although not estimated, it appears that substantial fatalities could be reduced. The European (EU) offset test procedure could potentially address many of the leg injuries, while other recent or future vehicle improvements, such as FMVSS No. 201 head protection or future advanced air bags will eliminate many of the other injuries and fatalities.

The analysis is based on relatively limited cases of drivers with air bags in NASS and findings may change with additional data.

## CRASH ENVIRONMENT

The agency's National Automotive Sampling System (NASS) files for the years 1988-96 were used to project the occupant injuries that will occur in an all air bag fleet. In the 1988-1996 NASS there are about 2700 vehicles with driver air bags in frontal crashes. The analysis will identify test conditions to simulate crashes with highest risk and frequency of injury/fatality. These test conditions can be used to analyze the safety performance of baseline vehicles and to assess potential countermeasures. The NASS is a statistical sample of the United States accidents investigated in detail. About 4,500 crashes per year are currently being investigated. The NASS files for these years differ from those of previous years in that only the more serious accidents qualified for inclusion into the files. Crashes involving air bag-equipped vehicles have been increasing along with the increasing installations. Between 1988 and 1996, the NASS teams investigated 44,368 crashes, representing an estimated 21 million crashes and 12 million injured vehicle occupants nationwide. In these crashes, 2,891 driver and 378 right, front passenger air bag deployments were investigated, representing an estimated 1,012,263 driver and 124,506 right, front passenger air bag deployments that occurred during that time frame.

When comparing drivers with air bags to those without air bags serious injury risk is slightly lower with air bags and belts and belts "as used", i.e., no discrimination for whether belts were or were not used (Figure 1, and Table 1.) However, for fatalities air bags have lower rates for all restraint conditions and

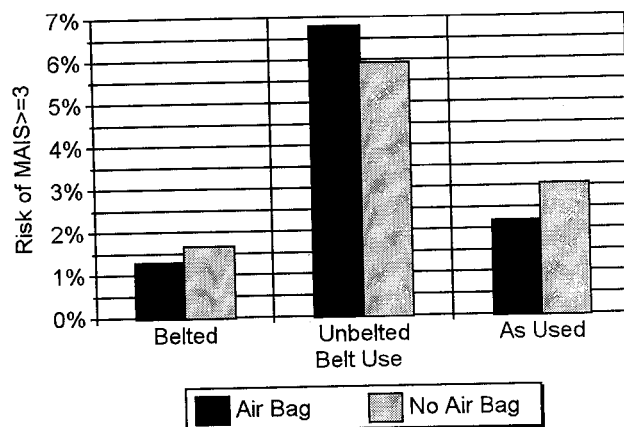


Figure 1. Serious Injury Risk by Restraint, Drivers in Frontals

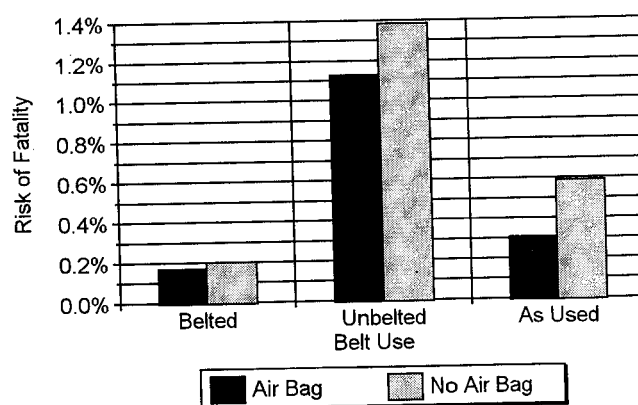


Figure 2. Fatality Risk by Restraint, Drivers in Frontals

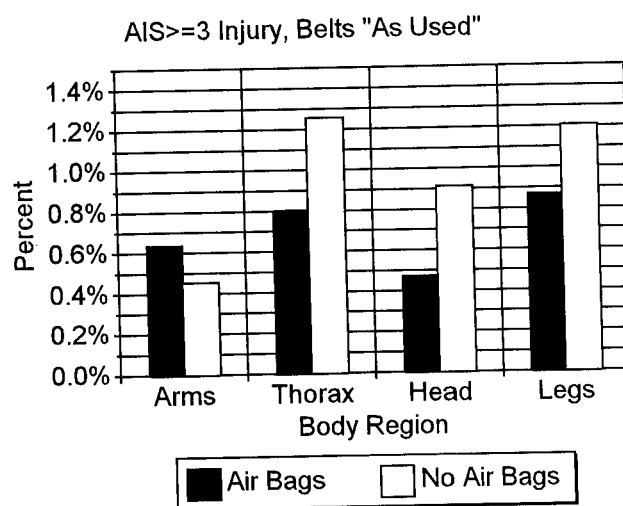
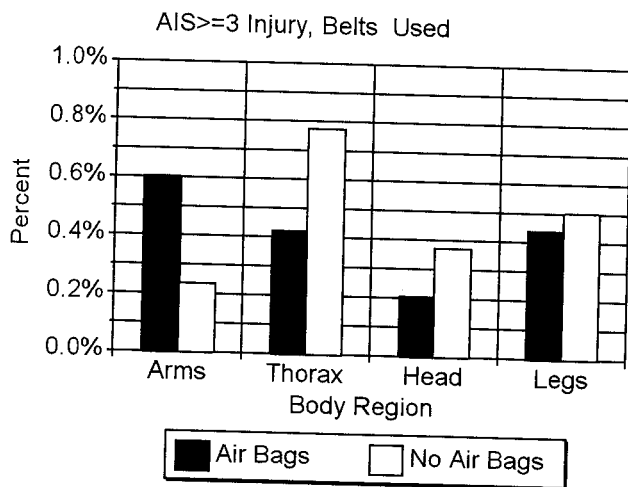


Figure 3. Serious-to-Fatal Injury Risk by Body Region, Belts "As Used"



**Figure 4. Serious-to-Fatal Injury Risk by Body Region, Belts Used**

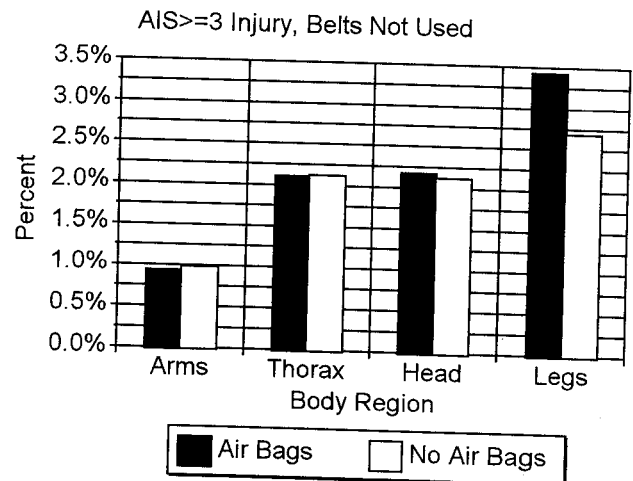
substantially lower for belts "as used" (Figure 2.)

Figures 3 to 5 and Table 2 show risk of serious injury by body region in frontal crashes for drivers of air bag equipped vehicles in air bag and non-air bag cars with and without belts. For serious-to-fatal injury and belts "as used" head, thorax and leg injuries are substantially lower with air bags. (Figure 3.) Arm injuries are somewhat higher with air bags. Since the majority of drivers in frontal impacts are belted (about 84 percent with air bags and 68 percent without) the injury risks by body region are similar when belts are used (Figure 4) as when "as used". For unbelted drivers there is no apparent reduction in serious to fatal chest or head injuries with air bags (Figure 5.)

Traditionally, fatality reduction has been the emphasis of the agency's research program. More recently, however, attention has been focused toward injury reduction, particularly for those injuries which lead to life long disabilities. This added focus includes the role of lower extremity and pelvic injuries in frontal crashes.

#### **Selection of Test Conditions Based on Crash Impact Modes**

An additional test procedure for increased frontal protection should simulate those impact modes in the "real-world" crash environment which result in highest frequency and risk of injury/fatality. Since FMVSS No. 208 sets performance requirements for full frontal impacts, the initial analysis focused on "offset", frontal



**Figure 5. Serious-to-Fatal Injury Risk by Body Region, Belts Not Used**

impacts as candidate accident modes for simulation. The accident analysis has been coupled with offset crash testing to determine which impact configurations produce the highest likelihood and frequency for injury/fatality.

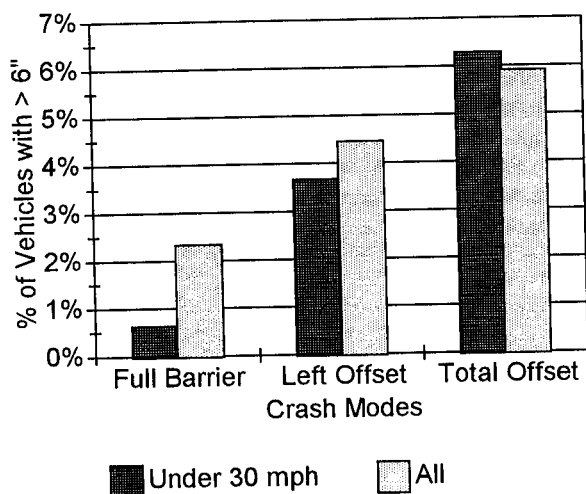
Drivers of all vehicles in 1988-1996 NASS were grouped by their general area of damage (GAD) and principal direction of force (DOF1) into a frontal impact population. Drivers were considered to be in frontal impacts if their vehicle sustained DOF1 between 11 and 1 o'clock or DOF1 was 10 or 2 and GAD1 was front or side with damage forward of the A-pillar. The frontal impact population is then separated into specific crash modes to identify potential impact configurations with high frequency and risk of injury to be simulated by crash test procedures. The frontal population was separated by direction of force (DOF) into collinear or oblique (left or right), by damage distribution into offset (left or right) or distributed, and by object contacted into another vehicle or fixed object. Counts in the paper are weighted unless noted. DOF is used to delineate collinear (12 o'clock), left (10 & 11 o'clock) and right (1 & 2 o'clock) oblique impacts. For frontal damage (GAD1=F), overlap is defined by the crash "D" variable when known and after 1989; otherwise, the primary specific horizontal location (SHL1) is used, and is separated into distributed ("D"=0 or SHL1=D), left ("D"<0 or SHL1=Y or L) and right ("D">0 or SHL1=Z or R) offset impacts. For those impacts with left or right damage (GAD1) the location must include the front corner of the vehicle (SHL1=F) and is entered as left or right 1/3 of the vehicle's front (equivalent to SHL1=L or R for GAD1=F.)

## Grouping Into Most Appropriate Test Procedure

The exposure population for frontal impacts, i.e., number of collisions, is based on 1988 to 1996 NASS to estimate the exposure for an all air bag fleet. Drivers in frontal collisions are grouped by impact conditions (DOF, damage distribution and crash partner) into the most appropriate test situation to simulate the type of collision.

For specifying impact conditions for a future frontal, offset test both crash pulse and intrusion are of comparable importance in occupant injury outcome. However, the agency is also currently addressing issues of what are the appropriate conditions for a full frontal test procedure in FMVSS No. 208, i.e., the full barrier, the current sled test or some other simulation test. For these types of tests, intrusion is of secondary importance and crash pulse alone is the important crash factor in the occupants injury outcome. To show a comparison of intrusion in full barrier type impacts and offset impacts, crash situations with intrusions of 6 inches or more into the vehicle compartment are assumed to compromise the compartment integrity and lead to serious or fatal injuries. As shown in Figure 6 the incidence of 6 inches or more intrusion is much greater in the offset impact modes than in the full barrier type modes, especially for crash severities less than 30 mph.

Figure 7 shows the test situations, the impact conditions for that test and the percentage of all frontal impacts represented. The first group of impact modes are



**Figure 6 - Percent of Vehicles with 6 inches or more Intrusion by Crash Mode**

those in which the test must account for both crash pulse and intrusion. The current frontal test is a full frontal impact into a fixed rigid barrier with impact angles on the car from -30 to +30 degrees. As shown in the figure, all collinear, distributed damage impacts and oblique, distributed damage, fixed object impacts with distributed damage are assumed to be best simulated by this test condition. The left offset configuration, either collinear or oblique direction of impact is assumed that all left offset impacts, either collinear or oblique, are best represented by this test condition. Also, it is assumed that the left oblique, vehicle-to-vehicle impact, with distributed damage is better simulated by the left offset test than by the barrier test. Not only may less than full overlaps often produce distributed damage, but the interaction of the vehicle and the propensity for higher intrusion is well simulated by this test even though there may be near distributed damage.

A right offset configuration would include right side impacts in the same way as left side impacts are included in the left offset test. About 9 percent of cars have offset, frontal damage which is opposite to the clock direction, i.e., left and right oblique impacts with right and left offset damage, respectively. Note that this would be the impact configuration for the "bullet" vehicle in a left or right oblique impact to the "target" vehicle, as shown in Figure 6. Based on the assumed groupings of vehicle impact conditions from above, the left offset test would represent about 34 percent of cars with air bags in "frontal" crashes, with right offset making up about 35 percent and full barrier about 22 percent.

If only crash pulse is considered, the full frontal fixed barrier accounts for the majority of impact modes in frontal crashes. Collinear, car-to-car crash tests at partial overlaps of 50, 60 and 70 percent, and a 30 degree oblique car-to-car impact with 50 percent overlap on a Chevrolet Corsica using a Honda Accord as the striking vehicle have been conducted. The car-to-car tests were conducted with both cars moving at about 56 kmph. Also, the agency has conducted an NCAP test using the Corsica, i.e., a 56 kmph, full frontal, rigid barrier test. The longitudinal compartment deceleration crash pulses are shown in Figure 8. The collinear 60 and 70 percent overlap crash tests appear to be well simulated by the full barrier impact along with the oblique impact at 50 percent overlap. However, for the collinear impact at 50 percent overlap the crash pulse appears to deviate somewhat from the full barrier pulse. Based on these comparisons, the collinear impacts with overlaps ranging from somewhere between 50 and 60 percent (say 55

## TEST CONFIGURATIONS TO SIMULATE CRASH MODES

Test	Configuration	Crash Modes (Intrusion/Pulse)	% of Frontals	Crash Modes (Pulse Only)	% of Frontals
Frontal Barrier FMVSS No. 208 +/- 30 Degrees		 All Fixed Object Fixed Object	21.7 %	 All > 55% Overlap All > 33% Overlap	74 %
Left Offset (0 to 30 Degrees)		 All All Vehicle	33.8 %	 All < 55% Overlap All < 33% Overlap	~13%
Right Offset (0 to 30 Degrees)		 All All Vehicle	35.3 %	 All < 55% Overlap All < 33% Overlap	~13 %
L. Obl./R. Off. R. Obl./L. Off. (+/- 30 Degrees)		 All All	8.8 %		

Figure 7. Possible Frontal Test Conditions and Impact Modes Addressed (1988-1996 NASS)

percent) to full overlap were classified as "full barrier-like" crashes. Since exact overlap dimensions are not available in all NASS cases, SHL1 also must be used. SHL1 is used to define a crash as "full barrier-like" for values of  $\frac{2}{3}$  and greater overlap.

Oblique, car-to-car impact tests have been conducted only at nominally 50 percent overlap impact conditions. As shown in Figure 8 the 50 percent overlap, oblique crash test actually produces as severe compartment deceleration crash pulse as the NCAP full barrier test, at similar impact speeds for the Corsica. Thus, in the absence of additional tests with varying proportions of overlap, it is assumed that oblique impacts can be represented by the full barrier test at overlaps of  $\frac{1}{3}$  and greater. The category of frontal impacts which qualify as "full barrier" (FB) like crash pulses, based on this analysis, include:

- Collinear with 55 percent and greater overlap or  $SHL1 \geq \frac{2}{3}$  when exact overlap dimension is not available
- Oblique (DOF1 12 o'clock) with  $SHL1 \geq \frac{1}{3}$

The 1988 through 1996 NASS-CDS files are queried for impact conditions shown above. Drivers in crashes with "barrier-like" impact conditions on the vehicle are compared to drivers of vehicles in all frontal crashes to determine what proportion of all frontal impacts are

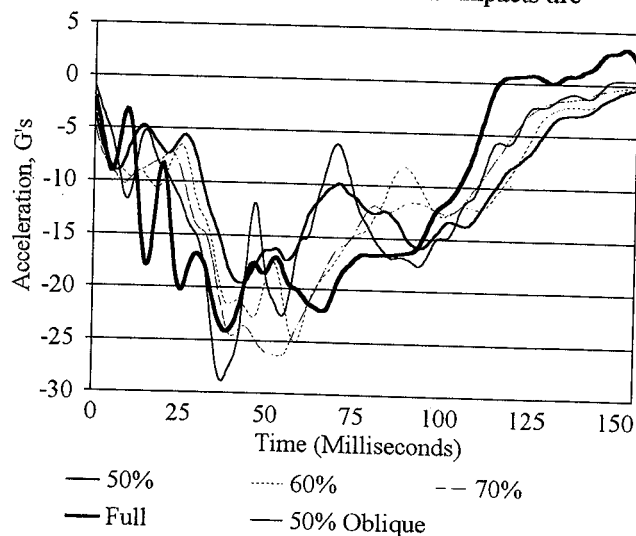


Figure 8. Crash Pulses by Overlap, Chevrolet Corsica, hit by Honda Accord and NCAP, at 56 Km/h

represented by "barrier-like" impact conditions. This comparison is made for:

- All drivers
- Drivers of vehicles with air bags, and MAIS $\geq$ 3 injuries

The 1988 through 1996 NASS-CDS files are queried for impact conditions which produce crash pulses which may be fairly well represented by the full barrier crash pulse, as discussed above (referred to subsequently as "barrier-like.") Drivers in crashes with "barrier-like" impact conditions on the vehicle are compared to drivers of vehicles in all frontal crashes.

For drivers in vehicles with air bags the proportion of driver in vehicles with "barrier-like" crashes as a percent of all frontal crashes is:

- 74 percent for all drivers
- 83 percent for drivers with MAIS $\geq$ 3 injuries
- 73 percent for driver fatalities

The remainder of the paper will consider those crash configuration groupings which account for both crash pulse and intrusion as factors in occupant injury.

### Injury Risk by Test Configuration

Comparing injury risk shows that for moderate and more severe injuries (MAIS $\geq$ 2) the injury risk is somewhat higher for vehicles in crashes fitting "left offset" than those described by "full barrier" (7.6 percent and 6.8 percent, respectively.) For serious and higher injuries (MAIS $\geq$ 3), the "full barrier" groupings has the highest injury rate (3.8 percent.) Left offset and right offset groups both have much lower serious injury rates of about 2.1 percent and 1.3 percent, respectively (Figure 9. And Table 3) Figure 10 shows fatality risk for the various impact modes grouped into appropriate test condition. These fatality rates are based on limited observations: 10 for full barrier, 38 for left offset, and 10 for right offset. The left offset grouping has much higher fatality risk (0.43 percent) than full barrier (0.25 percent) and almost four times that experienced by drivers with air bags in right offset modes (0.11 percent.)

An estimate of the annual injuries/fatalities which might be expected with an all air bag fleet is computed in Table 3 and shown in Figures 11 and 12. The estimates are based on the injury/fatality risks, shown previously,

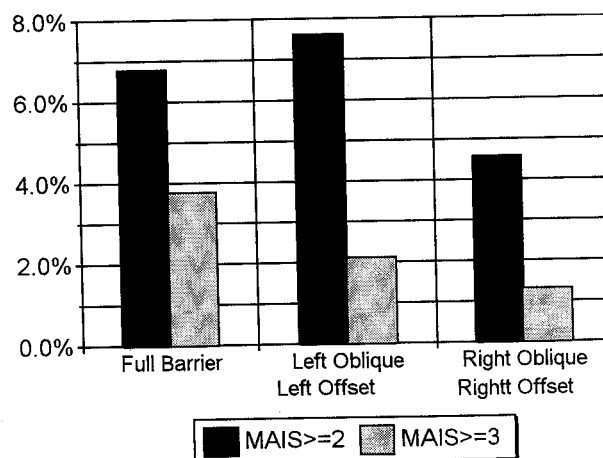


Figure 9. Injury Risk by Test Condition

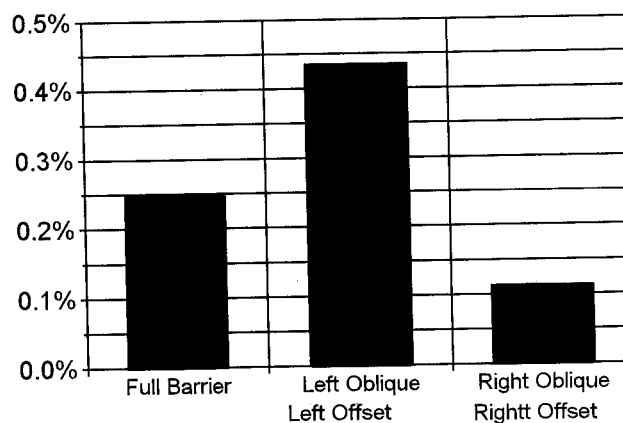


Figure 10. Fatality Risk by Test Condition

applied to the expected number of drivers with air bags in tow-away crashes in an average year (1988 through 1996 NASS divided by nine.) Based on these estimates the left offset impact modes would result in the highest number of drivers with MAIS $\geq$ 2 and fatal injuries (about 47,000 and 4,200, respectively.) Although full barrier type impacts would account for the highest number of MAIS $\geq$ 3 injuries (14,942) the left offset modes are only slightly less (13,042.)

Within the test groupings for left offset and right offset the effect of overlap on injury rate was assessed. As a rough approximation of overlap percent, an average car width of 66 inches is assumed for "L" in the offset formula:  $\text{Overlap} = 1 - (2 \cdot D / L)$ , where "D" is the distance from the vehicles center-line to the damage mid-point.

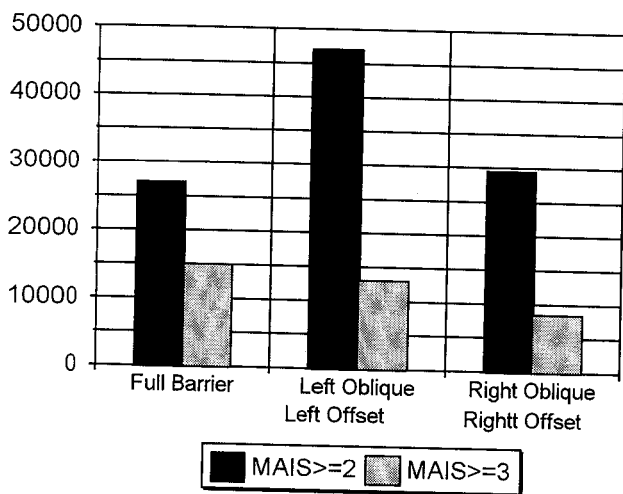


Figure 11. Estimated Annual Injuries by Test Condition

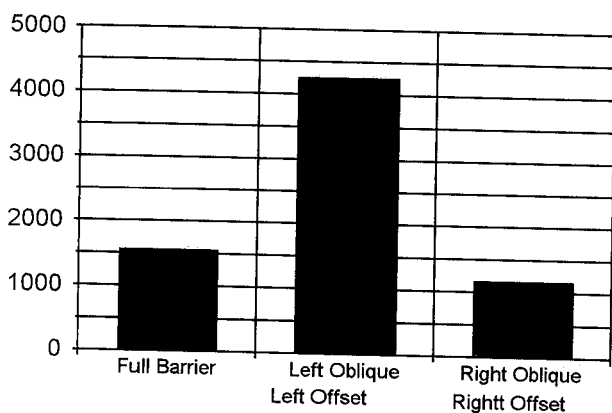


Figure 12. Estimated Annual Fatalities by Test Condition

Overlap is then separated into 1/3 or less of the car width, over 1/3 to 2/3 of the width and over 2/3 of the width. As discussed above, left and right damaged vehicles with damage to the front corner were grouped into the 1/3 overlap category. By using these damage width groupings, the SHL1 parameter, which is separated into damage width increments of one-third of the vehicle width, may be used when "D" is not known. The relatively low injury risk for configurations grouped under a left offset test appears to be due to low occurrence of MAIS<sub>≥3</sub> injuries in narrow overlap impacts. For left offset impacts the rate of MAIS<sub>≥3</sub> injuries is about 1.5% for 1/3 or less overlap (Figure 13 and Table 4.) Overlaps in the 1/3 to 2/3 range, also, result in fairly low injury rates for these configurations. At overlaps over 2/3, left offset impacts produce higher MAIS<sub>≥3</sub> injury rates, increasing to about 3.6 percent for over 2/3 overlap while right offset impacts at larger

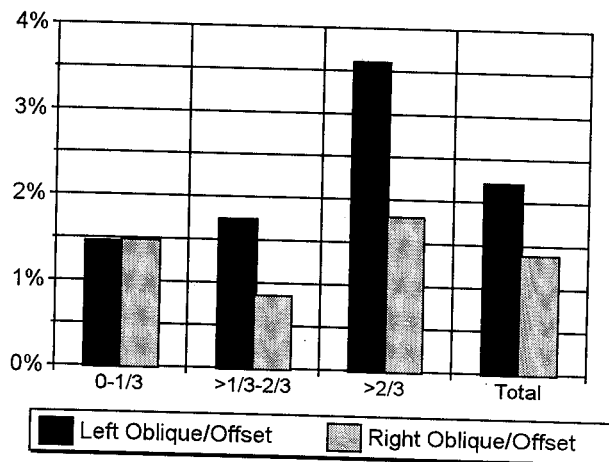


Figure 13. Serious-to-Fatal Injury Risk by Overlap

overlaps produce lower injury rates (1.8 percent for right offset.) The left offset impact at over 2/3 overlap produces the highest MAIS<sub>≥3</sub> injury rate of all offset impact modes considered (3.8 percent.)

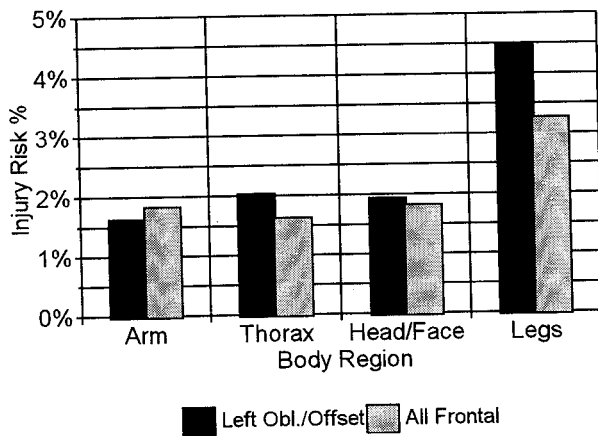
### Recommendation

Based on analysis of the NASS crash data files of drivers in frontal collisions with air bag restraints, the offset crash test which represents actual crash configurations with the highest frequency and risk of serious to fatal injuries is a left offset, vehicle-to-vehicle impact with substantial overlap (2/3 or greater.) The specific recommendations for impact angle and overlap percentage will be variables addressed in the crash test development phase of the program. The remainder of the paper assumes that this type of test condition will be selected as the offset procedure for the future and the analysis focuses on these crash modes.

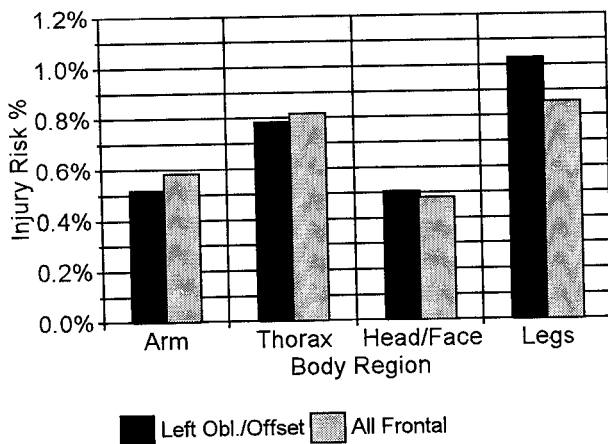
### Body Region Injury Assessment

Injury measures, criteria and instrumentation and the test surrogate itself should be selected based on the location and type of injuries experienced by the driver in frontal, left offset crashes.

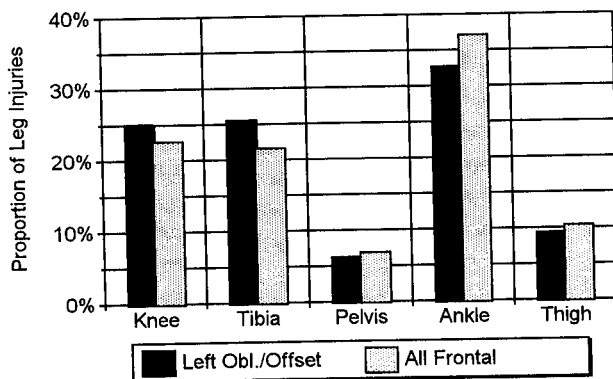
Injuries to specific body region are tallied by AIS level counting only the single, most severe injury to each individual body region which make up the general body region group (head, chest, arms and legs.) The risk of injury to a body region is the sum of injuries at the specific AIS level divided by all drivers in the crash mode. As shown in Figures 14 and 15 and Table 5, legs



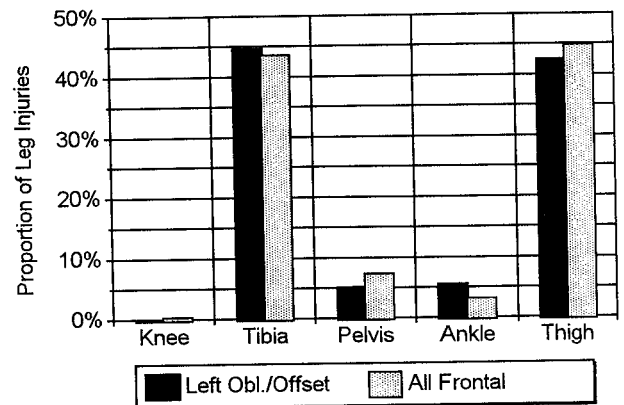
**Figure 14. AIS $\geq$ 2 Body Region Injury Risk, Left Offset and All Frontal Impacts**



**Figure 15. AIS $\geq$ 3 Body Region Injury Risk, Left Offset and All Frontal Impacts**



**Figure 16. Proportion of AIS $\geq$ 2 Leg Injuries**



**Figure 17. Proportion of AIS $\geq$ 3 Leg Injuries**

have a higher risk of AIS $\geq$ 2 and AIS $\geq$ 3 injury in left offset impacts than all frontals with other body regions having similar rates in both crash modes. Thus, reducing leg injuries should be a prime objective in addressing left offset crashes.

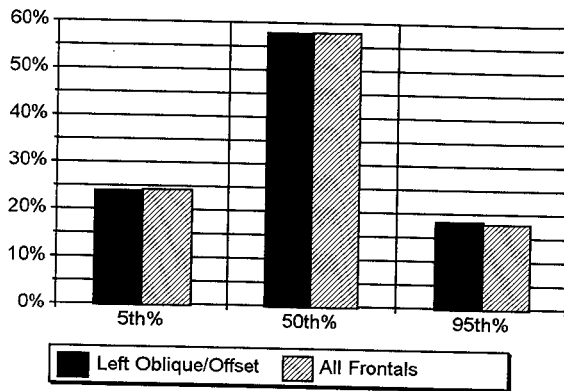
For drivers with air bags, AIS $\geq$ 2 leg injuries are separated into specific injury location in Figure 16 and Table 6. For these injuries, the ankle is most frequently injured followed by the knee and tibia, regardless of whether the impact is left offset or all frontals. Together these regions make up almost 90 percent of all AIS $\geq$ 2 leg injuries in left offset crashes. The tibia and femur dominate the severe leg injuries, with about 45 percent of leg injuries to the tibia and almost 43 percent to the femur, again, regardless of impact mode (Figure 17.) About 2% of moderate and serious leg injuries are fractures. Thus, a test surrogate should have appropriate hardware and be instrumented to assess AIS $\geq$ 2 ankle and knee injuries and AIS $\geq$ 3 tibia and femur injuries with the type of lesions listed.

### Injury Assessment by Size

The current frontal impact protection standard (FMVSS No. 208) assesses vehicle performance with a single size, 50th percentile, male dummy. An assessment of the crash environment by driver size was conducted to indicate whether there is a need to incorporate additional size dummies in future frontal test procedures. Drivers were grouped into three categories based on height of test dummies representing the 5th percentile female, 50th percentile male and 95th percentile male. The heights for each category are:

- 5th % group - less than 164 cm





**Figure 18. Crash Exposed Drivers by Size**

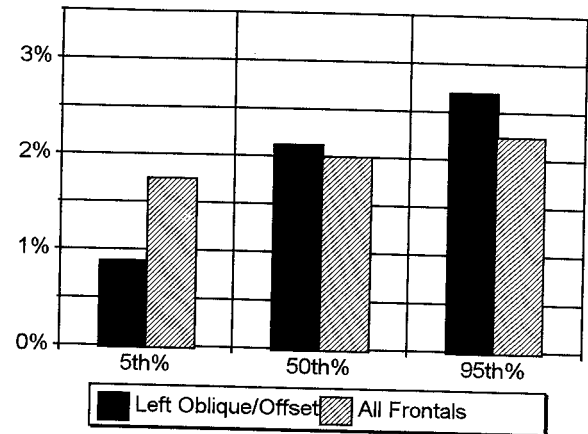
- 50th % group - 164 to 180 cm
- 95th % group - over 180 cm

The distribution of drivers with air bags grouped by height is shown in Figure 18 and Table 7 for left offset impacts and for all frontal impacts. The 50th % grouping represents about 58 percent of all involved drivers in left offset and all frontal impacts, the 5th % about 24 percent and the 95th about 18 percent.

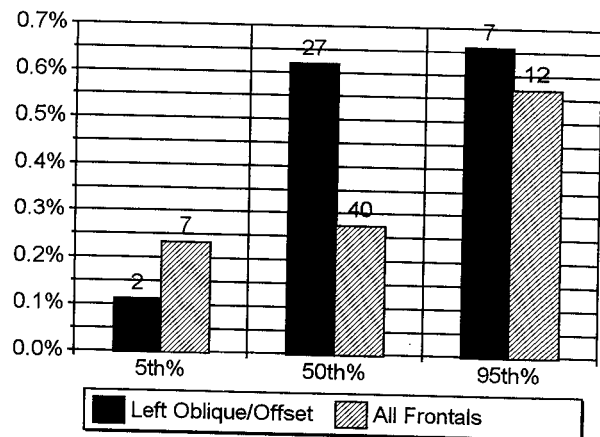
Figures 19 and 20 show MAIS $\geq$ 3 injury and fatality risk, respectively, by the three size groupings. Previous analyses have shown that smaller drivers, generally females, tend to have lower severity crashes and thus may have lower injury risk as a result. Because of the limited observations, as shown in Table 8, for assessing injury/fatality risk, no attempt is made to consider severity ( $\Delta V$ .)

The fatality risk is based on limited numbers with "raw" counts shown above each bar in Figure 20. The 5th percentile generally shows a lower injury/fatality rate for the left offset crash modes; however, this group experiences a higher MAIS $\geq$ 2 injury rate than the 50th percentile group. The 95th percentile shows highest risk for MAIS $\geq$ 2 and MAIS $\geq$ 3 injuries and fatalities. The higher injury risk for the 95th % grouping is due, at least in part, to the higher risk of leg and head injury (Table 8.) For all frontal impacts the 5th percentile exhibits similar injury risk as the other size groupings; however for fatalities the risk is much lower, but is based on limited observations.

The number of injuries and fatalities which might be expected annually for each size group with an all air bag fleet is estimated below for left offset impact modes. The estimates are based on current year Fatality Analysis



**Figure 19. MAIS $\geq$ 3 Injury Risk by Size**



**Figure 20. Fatality Risk by Size**

Reporting System (FARS, 1995) for fatalities and the NHTSA Final Regulatory Evaluation (FRE) on Air Bag Depowering for MAIS $\geq$ 2 injuries.

Table 9 presents the work sheet for computing the estimates. The annual exposure by size group is from 1988-1996 NASS for an average year which is multiplied by the injury risk (Table 8) to give an estimate of annual injuries/fatalities. Since the total driver fatalities based on NASS appears low, the estimates are adjusted by the computed number of driver fatalities in non-rollover, frontal crashes with an all air bag fleet based on 1995 FARS as shown in the table. The fatalities for left offset crash modes are adjusted to be consistent with the proportion of all frontal impact fatalities for these modes, computed earlier. Likewise, the number of injuries are adjusted based on the NHTSA Final Regulatory Evaluation (FRE) on Air Bag Depowering for MAIS $\geq$ 2 injuries, which predicted 120,000 annually. The same

adjustment factor for MAIS $\geq$ 2 injuries is also applied to MAIS $\geq$ 3 injuries. As shown, based on the assumed size groups, i.e., based on the division of sizes by the mid-point of the difference in height between successive dummy sizes, the 50th percentile group is the most populous and thus experiences the most injuries/fatalities. However, the 95th percentile group, although the least populous, experiences substantially more fatalities and MAIS $\geq$ 3 injuries than the 5th percentile group and has the highest injury and fatality risks.

Based on the assumptions made and the limited data on severe and fatal injuries, the 95th percentile group experiences a substantial number of injuries/fatalities and should be considered as an additional test surrogate to be used in a proposed left offset test procedure. The 5th percentile group, although experiencing less injuries, still has substantial numbers of moderate and severe to fatal injuries in this impact mode. A different definition of 5th, 50th and 95th percentile groupings, perhaps based on statistical groupings or more narrow height ranges for the 50th group would possibly lead to a different conclusion.

#### Benefits Assessment for an Improved Test Procedure

A preliminary method for estimating injury and fatality reductions for a left offset test procedure is proposed. This method assumes that for under 48 kph (the current FMVSS No. 208 test speed) the injury/fatality rates for drivers with air bags in left offset crash modes will be reduced to levels similar to those for drivers in full barrier modes. In other words, drivers with air bags in the proposed impact modes to be addressed by a left offset test would experience the same injury risk as drivers with air bags in impact modes addressed by the current requirement.

As shown in Figure 21 and Table 10 for speeds of 48 kph and less the MAIS $\geq$ 2 injury and fatality rates are higher for the left offset crash modes (8.6 and 0.2 percent) compared to full barrier modes (5.2 and 0.0 percent.) No fatalities occurred at 48 kph and less in full barrier type impacts. For MAIS $\geq$ 3 injuries the full barrier risk is actually higher than for the left offset for impacts at 48 kph and less (2.3 and 2.2 percent, respectively.)

As shown in the previous sections, arm injuries in the full barrier impact modes occur at a much higher rate than in impacts without air bags or even left offset impacts with air bags. Arm fractures and other less severe laceration and contusion type injuries occur quite frequently from aggressively deploying air bags. Another NHTSA research program is vigorously addressing problems associated with aggressive

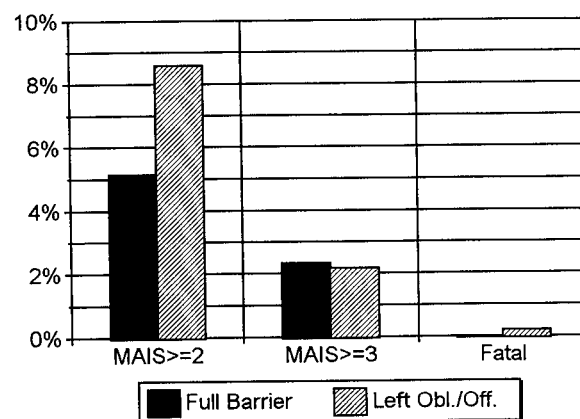


Figure 21. Driver Injury/Fatality Risk for All Injury, ≤ 48 KPH

#### Estimated Annual Driver Injury/Fatalities in Left Offset Impacts With Air Bags

INJURY LEVEL	Total	DRIVER SIZE GROUP		
		5th Percent	50th Percent	95th Percent
MAIS $\geq$ 2	45,924	11,796	19,819	14,309
MAIS $\geq$ 3	11,520	1,261	7,307	2,953
Fatalities	4,243	224	3,004	1,015

deployment of air bags on out-of-position occupants and arm injuries. This research program supported by this crash analysis is focused on improved frontal protection and not on resolving problems with aggressive air bag deployment. Since arm injuries are not the main concern of an alternative frontal test the analysis was repeated to compare injury risk when arm injuries are removed (Figure 22, Table 10.) Relative to the injury risk in full barrier type impacts this method shows a much higher risk for left offset impacts (1.66 percent for MAIS $\geq$ 3 and 7.86 percent for MAIS $\geq$ 2) than for full barrier (0.69 percent for MAIS $\geq$ 3 and 3.15 percent for MAIS $\geq$ 2.)

The percent decrease in injury risk for the left offset impacts compared to the full barrier impacts is shown in the following table. Since the estimate of fatality risk in impacts of 48 kph and less are based on few numbers and a total reduction in fatalities is unreasonable no

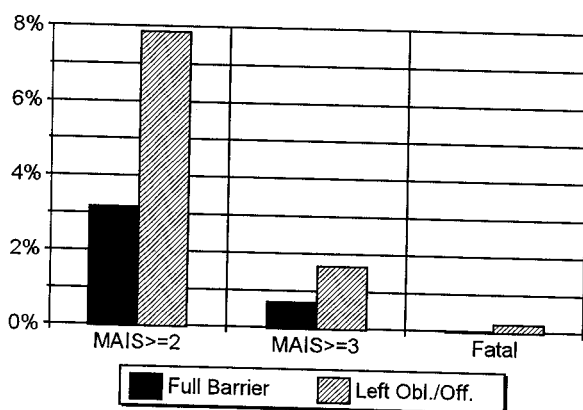


Figure 22. Injury/Fatality Risk Without Arm Injuries,  $\leq$ 48 KPH

numerical estimate is made for fatality reduction, except to say there appears to be potential for substantial reductions. Also, for drivers with air bags subjected to a left offset test procedure, an increase in MAIS $\geq$ 3 injuries in impacts is not expected and, thus, no change is predicted. The number of driver injuries and fatalities expected in left offset impacts with an all air bag fleet is shown in Table 10 and repeated below. The reduction in injuries/fatalities is then the percent change applied to these expected injuries and fatalities.

An analysis was also conducted to estimate the number of leg injuries which might be eliminated by a left offset test. Again, it is assumed that the benefit of adopting a left offset test procedure is an injury rate reduction for drivers with air bags below 48 kph to the injury rate experienced in full barrier type crashes. Table 11 shows the risk of receiving a leg injury of AIS $\geq$ 2 and of AIS $\geq$ 3 level for left offset and full barrier type impact modes. Drivers with air bags in full barrier type impacts below 48 kph have a lower risk of leg injury than those in left offset impacts by the percentages shown in the Table 11 worksheet. It is assumed that the number of injuries in NASS are below the annual nationwide count by the same factor as that used previously to estimate occupants. This factor is then applied to the NASS injury counts and the proportion of leg injuries computed to yield an estimate of leg injuries expected nationwide in one year. This annual estimate is then multiplied by the reduction in injury rate to give a rough approximation of number of leg injuries, AIS $\geq$ 2 and AIS $\geq$ 3, which might be eliminated with a left offset test procedure, as shown below. Based on this computation, over 11,400 AIS $\geq$ 2 and over 2,200 AIS $\geq$ 3 leg injuries could be saved.

#### Injury/Fatality Risk Difference: Left Offset Compared to Full Barrier, Under 48 KPH

Percent Change			Number in Left Offset		Reductions for Offset Test Procedure	
	<u>All MAIS</u>	<u>Arms Excluded</u>	<u>All MAIS</u>	<u>Arms Excluded</u>	<u>All MAIS</u>	<u>Arms Excluded</u>
MAIS≥2	- 40.0%	-59.9%	40568	34611	16,227	20,732
MAIS≥3	0% (+7.3%)	-58.7%	10889	8689	0	5,100
Fatality	Not Computed*		2664	2664	Not Computed*	
	<u>AIS≥2</u>	<u>AIS≥3</u>				
Annual Leg Injuries	24,169	4,834				
Reduction for Left Offset Test (Table 11)						
Percent	47.2%	45.8%				
<u>Annual Leg Injuries</u>	<u>11,416</u>	<u>2,215</u>				

\* There were 13 fatalities (unweighted) to drivers in left offset impacts under 48 kmph with no fatalities in full barrier type impacts.

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**TABLE 1 - Injury Risk by Restraint Condition, Drivers in Frontal Impacts, 1988-1996 NASS**

RESTRAINT		MAIS			Total
		2-6	3-6	Fatal	
All Air Bag (Belted+Unbelted)	#	78845	24979	3488	1142704
	Row%	6.90%	2.19%	0.31%	
	Raw#	614	294	64	2555
Non-Air Bag (Belted+Unbelted)	#	934506	287563	55423	9428597
	Row%	9.91%	3.05%	0.59%	
	Raw#	6732	3031	1078	23730
Air Bag and Belts	#	52082	12355	1610	953887
	Row%	5.46%	1.30%	0.17%	
	Raw#	347	149	29	1884
Belts	#	397403	101323	12230	6107706
	Row%	6.51%	1.66%	0.20%	
	Raw#	2391	897	224	12568
Air Bags and No Belts	#	24095	10612	1756	156198
	Row%	15.43%	6.79%	1.12%	
	Raw#	246	132	32	598
No Restraint	#	480798	166496	38787	2806459
	Row%	17.13%	5.93%	1.38%	
	Raw#	3919	1892	752	9728

**TABLE 2 - Injuries by Body Region for Drivers With and Without Air Bags**

Serious and Greater Injuries by Body Region (Most Severe AIS>=3)						
		Arms	Thorax	Head	Legs	Occupants Known AIS
Air Bag Belts "As Used"	Raw	66	110	64	142	2555
	#	7369	9314	5472	10058	1161513
	Risk%	0.63%	0.80%	0.47%	0.87%	
Non Air Bag Belts "As Used"	Raw	385	1433	1034	1236	23730
	#	43300	120297	87340	115450	9566033
	Risk%	0.45%	1.26%	0.91%	1.21%	
Air Bag Belts	Raw	51	42	23	71	1884
	#	5840	4070	1979	4236	970219
	Risk%	0.60%	0.42%	0.20%	0.44%	
Non Air Bag Belts	Raw	137	406	265	338	12568
	#	14647	48205	23219	31261	6220408
	Risk%	0.24%	0.77%	0.37%	0.50%	
Air Bag No Belts	Raw	13	57	40	64	598
	#	1474	3327	3438	5423	158090
	Risk%	0.93%	2.10%	2.17%	3.43%	
No Restraint	Raw	226	888	701	791	9728
	#	27812	59930	59948	75979	2825620
	Risk%	0.98%	2.12%	2.12%	2.69%	
Moderate and Greater Injuries by Body Region (Most Severe AIS>=2)						
Air Bag Belts "As Used"	Raw	172	183	199	321	2555
	#	21781	18701	20077	38286	1161513
	Risk%	1.88%	1.61%	1.73%	3.30%	
Non Air Bag Belts "As Used"	Raw	1246	2578	3612	2699	23730
	#	177592	296200	448255	309813	9566033
	Risk%	1.86%	3.10%	4.69%	3.24%	
Air Bag Belts	Raw	117	89	84	188	1884
	#	16371	9033	11603	27537	970219
	Risk%	1.69%	0.93%	1.20%	2.84%	
Non Air Bag Belts	Raw	459	976	1046	939	12568
	#	77453	148062	138056	125161	6220408
	Risk%	1.25%	2.38%	2.22%	2.01%	
Air Bag No Belts	Raw	49	81	111	120	598
	#	4875	7685	8199	10168	158090
	Risk%	3.08%	4.86%	5.19%	6.43%	
No Restraint	Raw	721	1395	2385	1557	9728
	#	90587	124360	283675	161361	2825621
	Risk%	3.21%	4.40%	10.04%	5.71%	

**TABLE 3 - Injury/Fatality Rates by Test Condition**

		Full Barrier	Left Obl./ Left Off.	Right Obl./ Right Off.	L&R Obl./ R&L Off.	Other	TOTAL
<b>MAIS&gt;=2</b>	#	15100	32841	20449	10445	10	78845
	Raw#	127	270	169	47	1	614
	Row%	19.2%	41.7%	25.9%	13.2%	0.01%	
	Risk	6.79%	7.61%	4.58%	10.25%	0.33%	6.54%
	Annual#	18175	31710	19882	11095	16	80879
	<b>Adjusted Injuries to FRE</b>	26967	47048	29499	16462	24	120000
<b>MAIS&gt;=3</b>	#	8367	9104	5870	1628	10	24979
	Raw#	71	130	75	17	1	294
	Row%	33.5%	36.4%	23.5%	6.5%	0.04%	
	Risk	3.76%	2.11%	1.31%	1.60%	0.33%	2.07%
	Annual#	10071	8791	5707	1729	16	26315
	<b>Adjusted Injuries to FRE</b>	14942	13042	8468	2566	24	39043
<b>Fatality</b>	#	548	1875	506	548	10	3487
	Raw#	10	38	10	5	1	64
	Row%	15.7%	53.8%	14.5%	15.7%	0.29%	
	Risk	0.25%	0.43%	0.11%	0.54%	0.33%	0.29%
	Annual#	660	1810	492	582	16	3561
	<b>Adjusted to FARS Annual</b>	1546	4243	1153	1364	39	8345
<b>Drivers with Air Bags</b>	#	222419	431302	446804	101858	2993	1205376
	Raw#	457	1067	895	265	5	2689
<b>Exposed Annual Drivers</b>	#	267716	416450	434416	108198	4921	1231701
	Row%	21.7%	33.8%	35.3%	8.8%	0.40%	

**TABLE 4 - Injury Risk by Overlap Proportion for Left and Right Offset Impacts**

		Left Offset			Total
		0-1/3	>1/3-2/3	>2/3	
MAIS>=2	#	8017	6553	18273	32843
	Raw#	68	76	126	270
	Row%	24.4%	20.0%	55.6%	
	Risk	5.01%	5.34%	14.23%	7.99%
	Annual#	11484	9387	26176	47048
MAIS>=3	#	2335	2136	4634	9105
	Raw#	37	39	54	130
	Row%	25.6%	23.5%	50.9%	
	Risk	1.46%	1.74%	3.61%	2.21%
	Annual#	3345	3060	6638	13042
Total	#	160134	122614	128445	411193
	Raw#	315	279	418	1012
	Row%	38.9%	29.8%	31.2%	
Right Offset					
MAIS>=2	#	5353	6650	8445	20448
	Raw#	48	42	79	169
	Row%	26.2%	32.5%	41.3%	
	Risk	3.66%	4.96%	5.91%	4.83%
	Annual#	7722	9594	12183	29499
MAIS>=3	#	2152	1137	2580	5869
	Raw#	20	15	40	75
	Row%	36.7%	19.4%	44.0%	
	Risk	1.47%	0.85%	1.80%	1.39%
	Annual#	3105	1641	3723	8468
Total	#	146108	133960	142960	423028
	Raw#	282	214	352	848
	Row%	34.5%	31.7%	33.8%	

**TABLE 5 - Injury by Body Region for Left Offset and All Frontal**

Body Region		Left Offset		TOTAL	
		AIS>=3	AIS>=2	AIS>=3	AIS>=2
Arm	#	2126	6669	6656	20929
	Raw#	32	75	66	173
	Risk%	0.5%	1.6%	0.6%	1.8%
Thorax	#	3220	8343	9329	18555
	Raw#	51	84	111	184
	Risk%	0.8%	2.0%	0.8%	1.6%
Head/Face	#	2077	7939	5472	20740
	Raw#	27	84	64	201
	Risk%	0.5%	1.9%	0.5%	1.8%
Legs	#	4227	18423	9761	37269
	Raw#	69	155	142	321
	Risk%	1.0%	4.5%	0.9%	3.3%
Total Injuries	#	11650	41374	31218	97493
	Raw#	179	398	383	879
Total Drivers	#	411192	411192	1142603	1142603
	Raw#	1012	1012	2554	2554

**TABLE 6 - Leg Injuries for Left Offset and All Frontal**

Left Offset									
		Knee	Tibia	Pelvis	Ankle	Thigh	Whole	Total	Drivers
AIS>=3	Raw#	1	27	6	2	42	2	80	1012
	#	0	2153	247	268	2051	105	4824	411192
	Row%	0.0%	44.6%	5.1%	5.6%	42.5%	2.2%		
AIS>=2	Raw#	34	46	25	76	44	7	232	1012
	#	7073	7189	1745	9220	2638	316	28181	411192
	Row%	25.1%	25.5%	6.2%	32.7%	9.4%	1.1%		
All Frontals									
		Knee	Tibia	Pelvis	Ankle	Thigh	Whole	Total	Drivers
AIS>=3	Raw#	2	53	18	5	80	2	160	2554
	#	26	4579	765	323	4706	105	10504	1142603
	Row%	0.2%	43.6%	7.3%	3.1%	44.8%	1.0%		
AIS>=2	Raw#	66	90	54	157	82	9	458	2554
	#	11650	11106	3536	19034	5293	745	51364	1142603
	Row%	22.7%	21.6%	6.9%	37.1%	10.3%	1.5%		



**TABLE 7 - Driver Exposure by Size Groups**

Test Condition		Driver Size			Total
		5th%	50th%	95th%	
Left Obl/Off	Raw#	194	512	169	875
	#	86118	208241	66045	360404
	Row%	23.9%	57.8%	18.3%	
All Frontals	Raw#	502	1231	426	2159
	#	238928	571491	176787	987206
	Row%	24.2%	57.9%	17.9%	

**TABLE 8 - Driver Injury by Size Group**

Test Condition	MAIS		Driver Size			Total
			5th%	50th%	95th%	
Left Obl/Off	2-6	Raw#	48	135	47	230
		#	7111	11948	8626	27685
		Row%	25.7%	43.2%	31.2%	
		Risk%	8.26%	5.74%	13.06%	7.68%
	3-6	Raw#	21	65	21	107
		#	760	4405	1780	6945
		Row%	10.9%	63.4%	25.6%	
		Risk%	0.88%	2.12%	2.70%	1.93%
	Fatal	Raw#	2	27	7	36
		#	96	1287	435	1818
		Row%	5.3%	70.8%	23.9%	
		Risk%	0.11%	0.62%	0.66%	0.50%
All Frontals	2-6	Raw#	116	290	96	502
		#	16821	37941	12236	66998
		Row%	25.1%	56.6%	18.3%	
		Risk%	7.04%	6.64%	6.92%	6.79%
	3-6	Raw#	49	145	48	242
		#	4176	11416	3948	19540
		Row%	21.4%	58.4%	20.2%	
		Risk%	1.75%	2.00%	2.23%	1.98%
	Fatal	Raw#	7	40	12	59
		#	557	1567	1008	3132
		Row%	17.8%	50.0%	32.2%	
		Risk%	0.23%	0.27%	0.57%	0.32%

TABLE 9 - Worksheet for Estimating Annual Injuries/Fatalities

ANNUAL EXPOSURE						
		Total	5th%	50th%	95th%	
Left Offset		416450	99510	240624	76316	88-95 NASS
All Frontal		1231701	298102	713029	220571	/8 Years
ANNUAL INJURIES/FATALITIES						
Left Offset						
MAIS>=2	31990	8217	13806	9967		
MAIS>=3	8025	878	5090	2057		
Fatalities	2101	111	1487	503		
All Frontal						
MAIS>=2	83591	20987	47338	15266		
MAIS>=3	24379	5210	14243	4926		
Fatalities	3908	695	1955	1258		
FARS 1995 Fatalities		8345	1995 Driver Fatalities in Light Vehicles			
FRE on DePowering		120000	1995 FARS driver fatalities		31786	
MAIS>=2 Injuries			- Non-rollover		23995	
			- Rollover		7791	
Adjustment Factors			Total non-air bag fatalities		31952	
All Frontal FataIs	2.14		- Non-rollover		24120	
MAIS>-2	1.44		- Rollover		7832	
MAIS>-3	1.44		Total air bag effectiveness		11%	
Left Obl./Off. FataIs*	2.02		- Non-rollover		14.6%	
* Adjusted to agree with Table 3 estimate of fatalities in left offset crashes			- Rollover		0	
		Total fatalities with air bags		28437		
		- Non-rollover		20606		
		- Rollover		7832		
		% Non-rollover fatalities in frontals		54%		
		1995 fatalities in frontals		11127		
		Frontal air bag effectiveness		25%		
		Frontal fatalities with air bags		8345		
ANNUAL INJURIES/FATALITIES (Adjusted)						
Left Offset						
		Total	5th%	50th%	95th%	
MAIS>=2	45924	11796	19819	14309		
MAIS>=3	11520	1261	7307	2953		
Fatalities	4243	224	3004	1015		
All Frontal						
MAIS>=2	120000	30128	67956	21916		
MAIS>=3	34998	7480	20447	7071		
Fatalities	8345	1484	4175	2686		

TABLE 10 - Comparison of Injury/Fatality Risk, Left Offset vs. Full Barrier

		MAIS Without Arm Injury					MAIS All Body Regions					
TEST			DeltaV			Known Total	Total	DeltaV			Known Total	Total
			<=30	>30	Unk.			<=30	>30	Unk.		
Full Barrier	Fatal	Raw#	0	6	4	6	10	0	6	4	6	10
		#	0	410	138	410	548	0	410	138	410	548
		Risk%	0.00%	20.60%	0.17%	0.33%	0.26%	0.00%	20.60%	0.17%	0.33%	0.26%
	MAIS>=3	Raw#	15	23	24	38	62	20	24	27	44	71
		#	838	969	4264	1807	6071	2840	1052	4475	3892	8367
		Risk%	0.69%	48.69%	5.13%	1.46%	2.93%	2.32%	52.86%	5.38%	3.14%	4.04%
	MAIS>=2	Raw#	37	31	42	68	110	46	33	48	79	127
		#	3852	1455	6250	5307	11557	6290	1979	6831	8269	15100
		Risk%	3.15%	73.12%	7.51%	4.27%	5.57%	5.15%	99.45%	8.21%	6.66%	7.28%
	Total	Raw#	223	34	180	257	437	223	34	180	257	437
		#	122152	1990	83186	124142	207328	122152	1990	83186	124142	207328
		Row%	98.40%	1.60%	40.12%	59.88%		98.40%	1.60%	40.12%	59.88%	
Left Offset	Fatal	Raw#	13	8	17	21	38	13	8	17	21	38
		#	447	265	1164	712	1876	447	265	1164	712	1876
		Annual#	2664	1579			4243	2664	1579			4243
		Risk%	0.20%	7.93%	0.65%	0.31%	0.46%	0.20%	7.93%	0.65%	0.31%	0.46%
	MAIS>=3	Raw#	55	18	38	73	111	66	20	44	86	130
		#	3779	902	2831	4681	7512	4930	975	3198	5905	9103
		Annual#	8689	2074			10763	10889	2153			13042
		Risk%	1.66%	27.01%	1.57%	2.03%	1.83%	2.17%	29.19%	1.77%	2.56%	2.21%
	MAIS>=2	Raw#	134	31	69	165	234	154	32	84	186	270
		#	17878	3091	7368	20969	28337	19526	3119	10196	22645	32841
		Annual#	34611	5984			40596	40568	6480			47048
		Risk%	7.86%	92.54%	4.09%	9.08%	6.89%	8.58%	93.38%	5.66%	9.81%	7.99%
	Total	Raw#	611	37	364	648	1012	611	37	364	648	1012
		#	227573	3340	180280	230913	411193	227573	3340	180280	230913	411193
		Row%	98.55%	1.45%	43.84%	56.16%		98.55%	1.45%	43.84%	56.16%	

**TABLE 11 - Leg Injuries in Full Barrier and Left Offset Crashes**

TEST	MAIS Level		DeltaV			Known Total	Total	
			<=30	>30	Unk.			
Full Barrier	MAIS>=3	Raw#	10	15	14	25	39	
		#	577	758	1082	1335	2417	
		Risk%	0.47%	38.09%	1.30%	1.08%	1.17%	
	MAIS>=2	Raw#	30	24	23	54	77	
		#	3427	1138	3214	4565	7779	
		Risk%	2.81%	57.19%	3.86%	3.68%	3.75%	
	Total	Raw#	223	34	180	257	437	
		#	122152	1990	83186	124142	207328	
		Row%	98.40%	1.60%	40.12%	59.88%		
	Left Offset	MAIS>=3	Raw#	36	11	22	47	69
#			1984	478	1765	2462	4227	
Row%			79.82%	20.18%	31.43%	68.57%		
Annual#			4834	1222			6056	
Risk%			0.87%	14.31%	0.98%	1.07%	1.03%	
MAIS>=2		Raw#	89	21	45	110	155	
		#	12100	2590	3733	14690	18423	
		Row%	91.57%	8.43%	28.99%	71.01%		
		Annual#	24169	2224			26393	
		Risk%	5.32%	77.54%	2.07%	6.36%	4.48%	
Total		Raw#	611	37	364	648	1012	
		#	227573	3340	180280	230913	411193	
		Row%	98.55%	1.45%	43.84%	56.16%		
Percent of drivers with AIS>=2 leg injury of all drivers with MAIS>=2 injury						56.1%		
Percent of drivers with AIS>=3 leg injury of all drivers with MAIS>=3 injury						46.4%		
Annual drivers with AIS>=2 leg injuries = 56.1%*(all drivers with MAIS>=2)						26393		
Annual drivers with AIS>=3 leg injuries = 46.4%*(all drivers with MAIS>=3)						6056		
Driver Leg Injuries in Left Offset Impacts								
	MAIS or AIS>=2		MAIS or AIS>=3					
	<=30	>30	<=30	>30				
Annual Leg Injuries	24169	2224	4834	1222				
Reduction Over Full Barrier (Table 10)								
Percent	47.2%		45.8%					
Annual Leg Injuries	11416		2215					

# OFFSET TEST PROCEDURE DEVELOPMENT AND COMPARISON

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Paper Number 98-S1-O-03

## ABSTRACT

Considerable worldwide attention has been directed to offset test development because past testing practices did not adequately address the structural integrity of passenger compartments for partial engagement car-to-car crashes or collisions into fixed narrow objects. National Highway Traffic Safety Administration (NHTSA) Research and Development has been conducting offset car-to-car and moving deformable barrier testing since the early 1980's in order to develop a offset test procedure that characterizes the crash environment in which serious injuries are projected to occur in an all airbag fleet. This paper will compare theoretical and actual results from car-to-car tests, the European test as used by the Insurance Institute for Highway Safety, and the NHTSA R&D test procedure using the moving deformable barrier.

## INTRODUCTION

Various test procedures are being used to evaluate the protection of occupants provided by production vehicles in offset crashes. This paper will discuss the research program conducted by NHTSA to develop an offset test procedure. In addition, other test procedures being widely used will be briefly described and compared to the NHTSA research procedure.

### European Test Procedure

The European Union has developed a test procedure (EU 96/79) for offset frontal crash testing [1] to address growing concerns that adequate protection is not provided by today's cars for most typical crashes involving some degree of offset and/or some degree of angle. This test was designed primarily to duplicate the crush patterns seen in real world crashes, thereby addressing intrusion induced injuries primarily to the lower leg region. This procedure designed by an international committee, has been widely accepted, and is used throughout Europe, Australia, and the U.S. This test consists of crashing the car into an

energy absorbing aluminum honeycomb face which is mounted to a fixed barrier. Forty percent of the front vehicle width engages the honeycomb at a crash speed of 56 km/h.

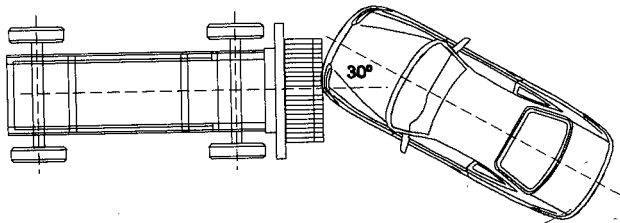
### Insurance Institute for Highway Safety (IIHS) Test Procedure

The IIHS has adopted the EU procedure except the crash speed was raised to 64 km/h to induce higher crush and evaluate the potential for more serious injuries. This higher severity crash test has also been adopted in Europe and Australia for comparing vehicle safety performance. The purpose of these tests are to provide information to consumers about the safety potential of the subject vehicle in offset crashes, particularly related to intrusion induced lower leg injuries. This paper will limit discussion to the IIHS procedure for which data are readily available for US vehicles.

### National Highway Traffic Safety Administration (NHTSA) Research Test Procedure Development

NHTSA has conducted an extensive crash test program to develop an offset crash test procedure to meet the following goals: (1) has the potential to evaluate serious injuries and fatalities that may occur in a fleet equipped with airbags and manual restraints, (2) closely duplicates the crash response, crush and occupant kinematics seen in real world type crashes that cause these serious injuries, (3) provides supplemental crashworthiness information to the full barrier test which more effectively evaluates restraint effectiveness, (4) assures compatibility between different size vehicles, and (5) is repeatable and reproducible. With these goals in mind, tests were conducted using a wide variety of airbag equipped vehicles crashed in various car-to-car and car-to-barrier configurations. Other papers have presented some of the results of this testing and crash data analysis used to establish the crash condition [2,3]. This paper will present the theory behind development of the test procedure and some of the most relevant comparisons of crash test data.

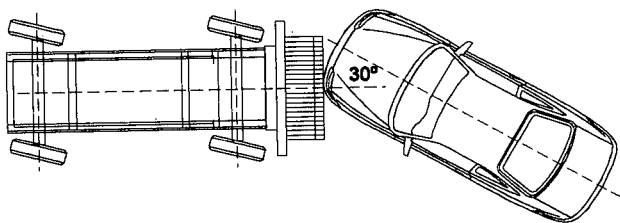
### **NHTSA 30° research test with both vehicles moving.**



**Figure 1.** Configuration of moving deformable barrier test with both vehicles moving.

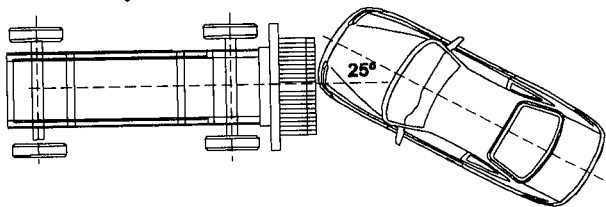
The basic test procedure chosen by NHTSA for development uses a MDB (moving deformable barrier), as described in FMVSS (Federal Motor Vehicle Safety Standard) 214, striking the front corner of the subject vehicle. This configuration was identified by crash data to represent crashes with a high risk of serious injury or fatality [2,3]. Figures 1 through 3 show the various crash configurations tested with the deformable barrier. To address the more severe crashes and the more serious

### **NHTSA 30° research test with MDB crabbed 15° and vehicle stationary.**



**Figure 2.** Configuration of moving deformable barrier test with struck vehicle stationary and barrier crabbed

### **NHTSA 25° research test with vehicle stationary.**



**Figure 3.** Configuration of MDB test with struck car stationary and barrier moving at oblique angle to centerline of car.

injuries, a closing speed of 113 km/h (70 mph) was chosen for most testing. For medium weight vehicles this collision is similar in speed to the NCAP test at 35 mph, but since the crash is offset and oblique, the crush to the subject vehicle is much more extensive. Smaller vehicles experience higher velocity changes due to their lighter mass, whereas larger vehicles are subjected to lower velocity changes using this test procedure. Similar differences exist in real world crashes between light and heavy vehicles.

Various test procedures were examined and compared in terms of dummy response, vehicle response and crush. These procedures were then compared to various car-to-car staged collisions. The car-to-car staged collisions and MDB tests were conducted at various overlap amounts, speeds and angles. In developing this test procedure, variations of the EU directive were considered. Early in the development of the NHTSA procedure, plans were made to test a variety of vehicles using the proposed EU fixed barrier. However, after conducting one test with a medium sized car, NHTSA concluded that the procedure would not address serious and critical injuries. Since the main objective of this research test was to address serious injuries, the MDB test was chosen in favor of the EU barrier.

Another NHTSA program investigated offset test procedures for different objectives. In this program, Congress directed the agency to investigate an offset test procedure for harmonization with European standards [4]. The agency has conducted several crash tests at lower speeds than those investigated in this research. These tests utilized the EU barrier, but the objectives of the test series was quite different from the research presented in this paper. The low severity offset testing focused on evaluating the benefits of adopting the EU procedure by comparing responses for 5th and 50th percentile dummies [5].

## **THEORY**

The following section will discuss the theoretical basis for development of the moving deformable barrier test. Energy absorbed by the subject car in the test procedure will be compared to theoretical energy absorbed in car-to-car crashes and full rigid barrier tests (as a baseline reference). Also the European test procedure will be compared in terms of energy absorbed by the subject car. The absorbed energy in the European and NHTSA tests will be discussed as it relates to its effect on compatibility for various size cars.

### Energy Absorption

Energy comparisons are appropriate for examining offset test procedures, because in offset crashes, crush levels are much higher due to partial engagement of the structure. To compare energy consumed by vehicles from several weight classes, energy consumed per unit weight (N-m/kg) is used for normalizing these values independent of weight. This method allows comparison between weight classes and accounts for the fact that cars are capable of absorbing energy proportional to their size. From another perspective, all vehicles consume the same amount of unit energy when crashed into a rigid barrier at any given speed, if rebound energy is either assumed negligible or constant. That is, energy in a barrier crash is directly proportional to mass according to the well known formula:

$$KE = \frac{1}{2} mv^2$$

where;

KE = kinetic energy  
m = mass of the vehicle  
v = velocity

To calculate energy absorbed by each car in car-to-car oblique collisions, the proportion of energy is empirically derived from an oblique crash test with two Tauruses. The proportion of energy is based on the post-test crush of each car according to the the following formulas:

$$E_1 = F d_1$$
$$E_2 = F d_2$$

where;

$E_1$  = The energy absorbed by vehicle 1  
 $E_2$  = The energy absorbed by vehicle 2  
F = average force exerted on the vehicles during crash (equal and opposite)  
 $d_1$  = the maximum crush distance for vehicle 1  
 $d_2$  = The maximum crush distance for vehicle 2

also:  $E_1/E_2 = d_1/d_2$  (energy ratio)

This ratio was calculated from film analysis motion of the CG's as 1.27, where vehicle 1 was the struck Taurus. That is the struck Taurus crushed 27% more than the striking Taurus. Expressed a different way, 56% of the total energy (1.27/2.27) was absorbed by the struck Taurus and 44% (1/2.27) by the striking Taurus. The striking car in an oblique crash absorbs less energy and is thus more aggressive to the struck car because the stiffer center of the striking car engages the softer corner of the opposing vehicle. This 56% to 44% proportion of total energy is

assumed for other vehicles, regardless of the vehicle size, due to lack of additional data.

### Compatibility

In this analysis, compatibility is assumed to be related only to energy sharing between vehicles in a multi-vehicle crash, although other factors such as geometry may influence compatibility. This and other factors are not considered in this analysis because compatibility differences of cars subjected to these offset test procedures is mostly a factor of crush energy. While it is recognized there are many other factors affecting compatibility such as geometry and crash mode (front-to-side and front-to-rear impacts for instance), this paper will focus only on front-to-front structural and mass compatibility. This approach for selection of a frontal test procedure is supported by crash data analysis, since most fatal and serious injury frontal crashes occur in front-to-front vehicle collisions. Therefore this paper will focus on theoretical crush energy consumed by the subject cars in various test procedures and car-to-car frontal collisions. Theoretical changes in velocity for these cars are also compared along with their crash deceleration environments (crash pulses). The results will help to understand the effects on future vehicle designs in response to the requirements (voluntary or regulatory) of various crash test procedures.

## TEST PROCEDURE

### Energy Comparison

Energy comparisons are made for the IIHS test procedure, the NCAP test procedure, and the NHTSA research test procedure. The EU and IIHS test procedure are identical except the IIHS procedure is closer to the speed of severe and injury causing crashes in the U.S. fleet. Conclusions made in this analysis for the IIHS test procedure apply equally to the EU test procedure and visa versa.

The NHTSA test procedure configuration shown in figures 2 and 3 is used to compute the energy dissipated by the honeycomb barrier face with the barrier moving at 113 km/h. To make the calculations, assumptions have to be made about the vehicle stiffness and thus the extent of honeycomb crush. For these assumptions two scenarios are used. One assumption is that honeycomb energy is absorbed proportional to the total energy in the crash, with the heaviest car fully crushing the honeycomb. Another scenario assumes the smaller cars are stiffer, thereby crushing the full depth of honeycomb similar to a heavier car. Therefore, in the second scenario, energy absorbed by the barrier is constant across the full range of vehicles. A

third scenario may be envisioned where the large car is too soft to crush the full extent of the honeycomb. Since this third scenario is unlikely, only the first two scenarios will be considered. The honeycomb force-crush properties are known from development work for the FMVSS 214 barrier [6].

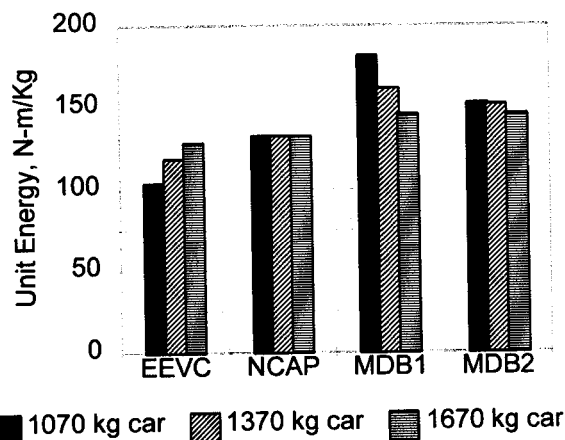
The energy absorbed by the FMVSS 214 face on the moving deformable barrier is estimated to be 155 kN-m, when fully crushed in the second scenario. The fixed deformable barrier used in the IIHS or EU 96/79 procedure is estimated to absorb only 65 kN-m based on its width and design [1]. Since the fixed deformable barrier face is capable of absorbing a much smaller quantity of energy than the moving deformable barrier face and the maximum force to crush the honeycomb is less than the maximum force exerted by car frontal structures, it seems reasonable to assume in the EU type test that all available honeycomb energy was absorbed for all size vehicles. Note this assumption may not be valid for lower speed crashes, particularly involving smaller vehicles.

Figure 4 shows the results of the unit energy calculations for the IIHS test procedure at 64 km/h, the NCAP test at 56.5 km/h (for reference), and the moving deformable barrier at 113 km/h, resulting in a 56.5 km/h  $\Delta v$  for equal weight cars. The unit energy absorbed by cars tested with the moving deformable barrier using the two previously stated assumptions about extent of energy absorption is shown on figure 4 as MDB1 and MDB2. MDB1 denotes the case where the honeycomb absorbs energy in proportion to the total energy of the crash 124 kN-m, 141 kN-m, and 155 kN-m for the light medium and heavy cars, respectively. The bars labeled MDB2, refer to the case where energy absorbed by the honeycomb is constant at 155 kN-m. Looking at the bar chart for MDB1 and MDB2 shows that MDB1 tests require less energy absorption for cars as weight increases, whereas MDB2 tests require similar energy absorption by weight of car. To explain the MDB1 case in physical terms, it is typical for larger cars to crush less, while small cars crush more in car-to-car crashes due to stiffness differences. The same phenomena may occur in the MDB testing with the honeycomb absorbing more energy when struck by the large car (i.e. less energy absorbed by large car) and less energy when struck by the smaller car. This situation is far less than ideal for the small car, because intrusions would be disproportionately large for the small car. A more ideal situation for compatibility is one in which control of intrusion is balanced against a stiffer structure. The result would be as seen in figure 4 as MDB2, in which the smaller car is actually stiffer than the larger car.

As shown in figure 4, crash testing with the EU

barrier requires less unit energy to be absorbed by smaller vehicles than by larger vehicles. NCAP testing, which represents hitting a fixed object or equal weight car, shows a constant unit energy requirement for all size cars. In

## Unit Energy by Test Procedure

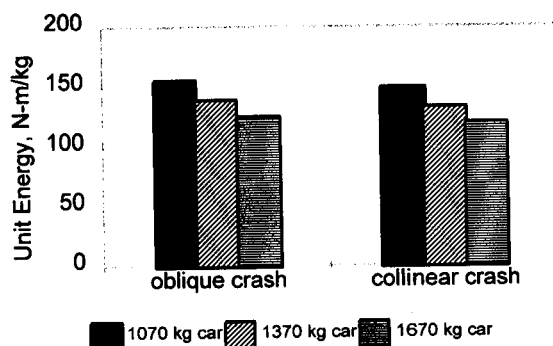


**Figure 4.** Unit energy absorbed by subject vehicles subjected to various test procedures.

car-to-median weight car testing more unit energy is typically absorbed by small cars than large cars.

Figure 5 shows the comparison of energy absorbed by the subject car in both collinear and oblique offset tests. Notice that the energy requirements imposed by the IIHS test is opposite in the trend by car size to that required by car to car or deformable barrier testing. Since energy absorbed is proportional to the amount of crush, small cars tested with the EU barrier may crush less than in most

## Unit Energy by Car Size Struck by 1370 kg Car



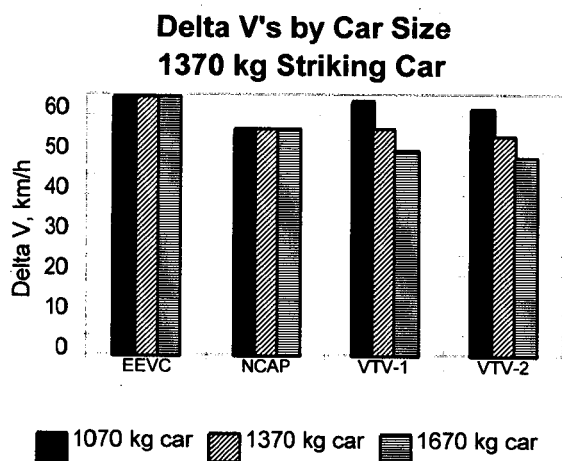
**Figure 5.** Comparison of unit energy absorbed by cars when struck by a medium size (1370 kg) car.



typical real world crashes of comparable speed. Since the objective of the IIHS test is to compare test vehicles under extensive crush conditions simulating offset collinear collisions, the results may be misleading in favor of the smaller cars. To compensate for this discrepancy, test velocity may be adjusted inversely proportional to weight. Alternatively, the test severity may be reduced and the honeycomb stiffened to increase the proportion of energy absorbed by the barrier when struck by larger cars, and to decrease the proportion of energy absorbed by the barrier when struck by small cars.

### Delta V Comparison

The difference in delta V levels can be seen in figure 6. Delta v's are compared for the various test procedures and car-to-car crashes. The delta v's shown as VTV-1 represents the subject vehicle struck by a medium weight car in a collinear crash with each vehicle moving at 56.5 km/h or the MDB moving at 113 km/h striking the stationary vehicle. The delta v's shown as VTV-2 represent the subject car moving at 56.5 km/h struck by a medium weight (1370 kg) car or a moving barrier at 56.5 km/h in an oblique configuration as shown in figure 1. Figure 6 shows that the IIHS test procedure produces a delta v for all size vehicles slightly higher than the small car delta v when struck by the moving barrier or medium weight car. This higher delta v is necessary to compensate



**Figure 6.** Delta V's by crash mode for various test configurations.

for the energy absorbed by the barrier. The MDB test procedure produces delta v's identical to the car-to-car crashes.

### Compatibility Comparison

In the IIHS test procedure as previously discussed, the unit energy absorption required for a small car is much less than for a large car. Since this trend is opposite to car-to-car crashes, the results of meeting such a test requirement may be counter productive. It may be possible to design the structure of a small car to crush more and still perform well in this test relative to a large car in the test. Since the deformable fixed barrier test imposes higher unit energy requirements on the large cars, it is also possible for the larger cars to become stiffer to meet acceptable voluntary or regulatory performance requirements. In contrast, fixed rigid barrier testing requires that the unit energy remain constant across the range of vehicle sizes. Therefore, we would expect neither an improvement nor a decrease in vehicle compatibility from fixed barrier testing.

Since the moving deformable barrier test imposes a harsher crash environment on the smaller vehicles due to higher energy absorption and higher delta v (representative of the overall crash environment), the natural tendency to meet the test requirements will be to increase the stiffness of the smaller cars (as well as improving restraints) to compensate for the increased crush. The unit energy requirements for large cars also remain high compared to fixed barrier testing, even though the change in velocity is lower. Additionally the energy requirement for a large car is independent of its structural stiffness as seen by the energy comparison of figure 4 for large cars tested with the MDB. However, a large stiff car would see a harsher crash environment in terms of crash pulse in this procedure. Therefore in meeting the requirements of this procedure large car stiffness would likely be reduced or maintained at a minimum level that would still mitigate the compartment intrusion. Therefore fleet compatibility would tend to improve in response to the moving deformable barrier test procedure in order to optimize the vehicle structure to provide an acceptable or high level of occupant protection. Physically, small cars would be required to reduce compartment intrusion through improved structural stiffness while imposing more crush (energy absorption) on the moving deformable barrier while heavier cars would maintain the same or perhaps softer structures in order to balance compartment integrity with crash pulse severity. In the MDB test the smaller vehicle is exposed to higher velocity change due to mass. This phenomenon which is not controllable by improved design, combined with a poor structure would allow for excessive crush resulting in an extremely harsh crash environment in terms of survivability. The only available countermeasure for a light vehicle would be to increase structural stiffness (and improve restraints) such that the honeycomb is fully

crushed (to the maximum extent) without excessive stiffness which would cause even higher occupant loading due to increased acceleration of the compartment. The larger vehicle on the other hand experiences a different crash environment. The higher mass which reduces velocity change also requires higher energy absorption. Therefore the near total crush of the honeycomb is very easy to achieve, but excessive crush and bottoming of the honeycomb structure will result in very high compartment deceleration. To improve occupant protection, softening the structure and/or improving restraints may be necessary.

## CRASH TESTING

### Energy Comparison

The calculated unit energy consumed by Ford Taurus vehicles in actual crash tests is shown in Table 1. Table 1 also summarizes the test configurations and data for these crash tests. The proportion of energy absorbed by each Taurus in a single car-to-car crash test was determined by the ratio of post-test crush measurements as previously discussed, and is shown in table 1. The unit energy level of 164 kN-m/kg for the oblique car-to-car Taurus test is significantly higher than the 155 kN-m/kg for the large car in the MDB1 test shown in figure 4. This difference is due to a higher speed and a heavier bullet vehicle in the Taurus tests. The Taurus test weight was approximately 1570 kg and the moving deformable barrier weighs 1595 kg to approximately match the Taurus weight. In this crash test, the honeycomb absorbed energy

was assumed to be at the maximum of 155 kN-m as previously described for MDB1. The unit energy absorbed by the Taurus in the MDB test was calculated as 164 kN-m/kg, slightly higher than in the car-to-car test. In contrast, the calculated unit energy absorbed by the Taurus was 125 kN-m/kg in the EU test and 132 kN-m/kg in the NCAP test. While these energies are similar to each other they are significantly lower than the car-to-car oblique test and the MDB test, but are comparable to the car-to-car collinear test at 132 kN-m/kg. This difference is explained by the different crushing of two cars in an oblique and offset crash where one vehicle is striking the relatively soft corner of the opposing vehicle (subject vehicle in this study) with its stiffer mid front section.

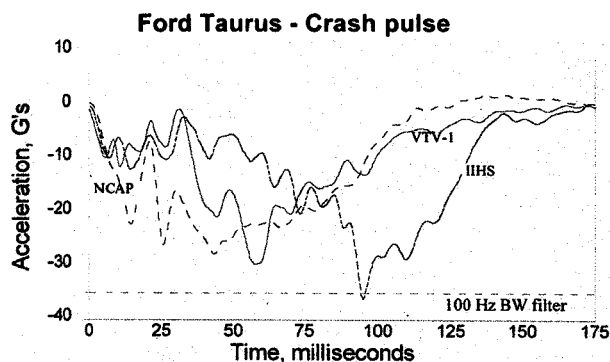
### Crash Pulse Comparison

The following will compare structural and dummy response for the 1992-1995 Ford Taurus (identical model years) models which were crash tested in five crash configurations. The crash conditions were: (1) car-to-car collinear offset at 50% overlap and 35 mph (abbreviated VTV-1); (2) a rigid barrier NCAP test at 35 mph and full engagement (abbreviated NCAP); (3) a 40 mph and 40% overlap into a deformable fixed barrier (conducted by Insurance Institute for Highway Safety abbreviated IIHS); (4) a car-to-car 30 degree oblique offset at 59% overlap and each vehicle moving at 38 mph (abbreviated VTV-2); (5) and a moving deformable barrier to car 30 degree oblique offset at 53% overlap and each vehicle moving at 36 mph (abbreviated MDB).

**Table 1. 1992-1995 Ford Taurus Test Conditions and Results**

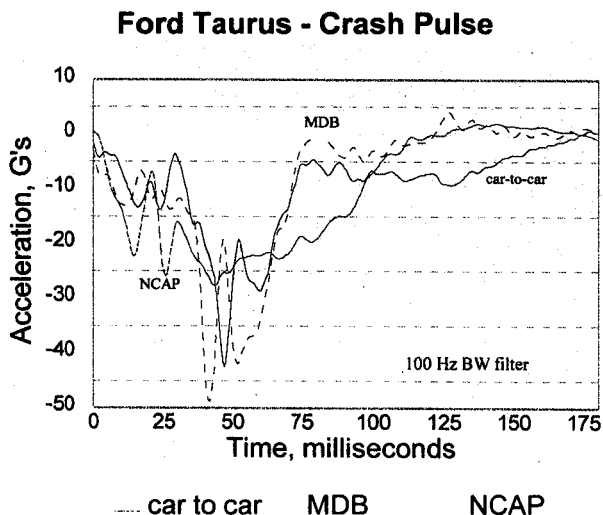
	Test Conditions				Driver ATD Response			
	Unit Energy, N-m/kg	Test Configuration	Closing Speed, km/h	Overlap, %	HIC	Chest 3 ms Clip	Max Femur, Newtons	Max Tibia Index
Car-to-car, collinear	132	collinear	113	50%	530	45.4	5654	1.0
Car-to-car, oblique	164	see figure 1	119	59%	411	51.0	5824	1.7
MDB-to-car	170	see figure 1	113	53%	461	54.8	6708	2.4
MDB-to-stationary car	161	see figure 2	111	47%	497	62.5	7532	2.3
MDB-to-stationary car	168	see figure 2	113	68%	620	61.8	15620	1.4
MDB-to-stationary car	130	see figure 2, except @ 45°	109	65%	363	44.9	7223	1.6

The crash pulse for the car-to-car collinear, NCAP, and EU tests are shown in figure 7. Note that the car-to-car 50% test and the NCAP test are somewhat



**Figure 7.** Comparison of Taurus Crash Pulse for car-to-car collinear offset, NCAP, and IIHS crash tests.

similar in peak amplitude, but the peak occurs approximately 14 milliseconds later in the car-to-car collinear test. The crash pulse resulting from the IIHS test does not appear similar to either the NCAP or the car-to-car crash pulse. In the IIHS test the dissipation of energy occurs much more slowly and the peak acceleration is higher and much later.

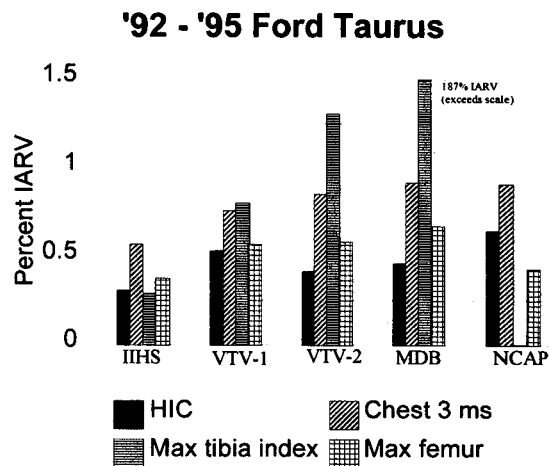


**Figure 8.** Comparison of Taurus crash pulse for car-to-car oblique, NCAP, and moving deformable barrier crash tests.

Figure 8 compares the crash pulse for the car-to-car oblique test with the moving deformable barrier and NCAP tests. This figure shows that the moving deformable barrier test matched the car-to-car oblique (VTV-2) response very well. The peak accelerations occur at nearly the same time and are similar in amplitude. In contrast, the difference in peak acceleration between the NCAP and either of the two other Taurus tests became quite apparent. However, the overall response from the Taurus NCAP agreed fairly well with the car-to-car and MDB tests.

### Dummy Response and Kinematics

Figure 9 shows the comparison of dummy responses for the five crash test conditions for the Taurus. Values are expressed in percentages of "injury assessment reference values" or IARVs. These reference values are defined in FMVSS 208 except for the "tibia index" which uses a reference value of 1.3, as defined by the EU 96/79 standard. The tibia index is computed by the formula:



**Figure 9.** Percent IARV for Taurus in various crash configurations.

$$M_t/225 + F_z/35,900$$

where,

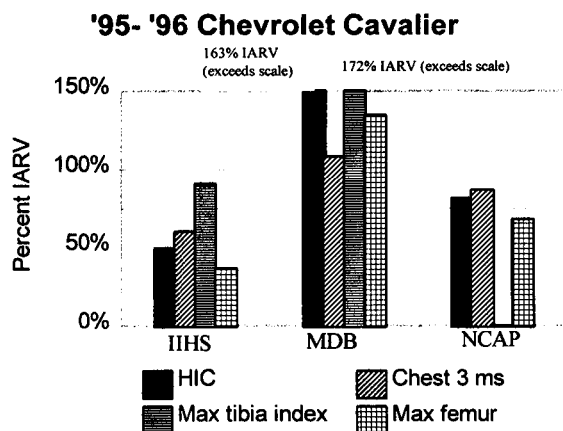
$M_t$  = resultant upper or lower tibia moment in Newton-meters

$F_z$  = upper or lower tibia compressive force in Newtons.

A very good match is noted between the oblique car-to-car (VTV-2) dummy responses and the MDB test. This is especially true for the head, chest and femur comparisons, but the tibia response was 43% higher in the MDB test. This match is expected since the MDB

test was designed to duplicate this car-to-car test mode. As previously noted, the crash pulses of these two tests also matched well. It does become apparent that due to the limited crush of the MDB honeycomb, the MDB test is slightly more aggressive, resulting in slightly higher vehicle response and higher dummy femur response. The IIHS test responses are compared to the offset collinear (VTV-1) response for which it was designed to replicate. Referring to figure 7 shows very little similarity between the crash pulses from these two tests. Comparing dummy responses from figure 9 shows much lower dummy responses for all major injury indicators, including the leg values, even though the IIHS crash is at a significantly higher speed.

Comparing the NCAP test to the other test configurations shows the NCAP pulse more closely resembling the oblique car-to-car (VTV-2) pulse than any of the others. The peak acceleration for the car-to-car collinear (VTV-1) pulse and NCAP pulse are similar in amplitude, but significantly shifted in time (approximately 14 milliseconds). Dummy chest responses were also similar for the NCAP and oblique car-to-car test (VTV-2), but head and femur responses differed significantly. These differences were most likely due to intrusion and dummy kinematics due to the angled crash configuration in the car-to-car test. Lower leg instrumentation was not available for the NCAP test and could not be compared. Another vehicle that was tested with the deformable moving barrier in NCAP and by IIHS was the '95 - '96 Chevrolet Cavalier. The results for the dummy in these three crash tests are shown in figure 10.



**Figure 10.** Percent IARV for '95 - '96 Chevrolet Cavaliers subjected to three crash tests.

## CONCLUSIONS AND RESULTS

The IIHS test procedure was compared to the NHTSA MDB test procedure in terms of energy absorption, dummy response, and vehicle compartment accelerations. The IIHS test series has shown that lower extremity injuries are addressed, but the MDB test series addresses the lower extremity injuries as well. Additionally, the MDB addresses the serious injuries that are likely to occur in an all airbag fleet. It was shown that the MDB test produces compartment and dummy responses that are similar to responses seen in comparable severity car-to-car crashes. It was also shown that the deformable barrier has the potential for improving compatibility between different vehicles in high-speed frontal collisions. Therefore, the moving deformable barrier test appears to be a good alternative test method to assure better front-to-front compatibility. This test method also provides good correlation with real world crashes, evaluates the potential for serious injuries and fatalities, and complements the full barrier test.

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# MODELING OF AN INNOVATIVE FRONTAL CAR STRUCTURE: SIMILAR DECELERATION CURVES AT FULL OVERLAP, 40 PER CENT OFFSET AND 30 DEGREES COLLISIONS

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## ABSTRACT

The improved frontal crashworthiness of cars necessitates totally new design concepts, which take into account that the majority of collisions occur with partial frontal overlap and under off-axis load directions. Realistic crash tests with partial overlap have shown that conventional longitudinal structures are not capable of absorbing all the energy in the car front without deforming the passenger compartment. The reason for this is that the structure of the longitudinal members is specifically designed for meeting the more relaxed requirements of the compulsory full overlap test, in which both longitudinals are loaded axially.

Increased protection for the entire collision spectrum can be obtained by a frontal structure consisting of two special longitudinal members, which combine a higher bending resistance without increasing the axial stiffness. In addition the longitudinal members are supported by a cable connection system for symmetric force distribution. If only one of the longitudinal members is loaded during a partial overlap crash, the cable connection system will force the other longitudinal member to crumple as well. This results in normal programmed energy absorption. With this revolutionary concept a complete frontal car structure is designed with almost the same stiffness for all overlap percentages and impact angles, resulting in one crash pulse which can be optimized for minimal injury of the occupants.

The influence of various crash situations on the amount of energy absorbed by this total vehicle model and specified for important structural parts will be demonstrated by means of numerical simulations. Also important construction details, necessary for a well functioning of the designed cable supported frontal car structure, will be mentioned.

## INTRODUCTION

For improved frontal car safety it is necessary to design a structure that absorbs enough energy in each realistic crash situation. To protect the occupants, the

passenger compartment should not be deformed and intrusion must be avoided too. To prevent excessive deceleration levels, the available crush distance in front of the passenger compartment must be used completely for a predetermined crash velocity. This implies that in a given vehicle concept the structure must have a specific stiffness. Normally, the two main longitudinal members will absorb most of the crash energy with a progressive folding deformation of a steel column. The main problem is that in real car collisions these two longitudinals often are not loaded axially in a synchronous fashion. The majority of collisions occur with partial frontal overlap, in which only one longitudinal is loaded, or with an off-axis load direction. This implies that most longitudinals fail under a premature bending collapse rather than a much more energy absorbing progressive folding pattern. This gives rise to two design conflicts. The first conflict is that the same amount of energy must be absorbed with either one or with two longitudinals. The second conflict is that the same amount of energy must be absorbed in the case of an off-axis impact angle as in the case of a normal incidence impact. These problems can not be solved by just increasing the stiffness of the longitudinals in such a way that each longitudinal is capable of absorbing all of the energy. To absorb enough energy, a stiff longitudinal is needed for the offset crash in which normally only one longitudinal is loaded. The same longitudinal must be more supple in case of a full overlap crash, since both longitudinals must not exceed the desired deceleration level (Witteman 1993). In addition, a stiff longitudinal is needed to absorb enough energy in an off-axis load direction (e.g. a crash test with a 30 degrees barrier) resulting in a higher bending resistance to help transform off-axis loads into axial loads and to prevent a bending collapse. The same but more supple longitudinal is needed in the case of a normal axial load to avoid overly high deceleration forces.

To solve this design problem with its contradictory requirements, a new approach is needed in which the design for the frontal car structure is decomposed into separate parts each fulfilling its own function. The combination of these parts yields a complete vehicle

structure which meets the requirement that in each crash situation (off-axis, offset and full overlap) nearly the same energy is absorbed and a similar deceleration level is obtained.

The next section presents a design solution based on this approach. It consists of a longitudinal with conventional axial stiffness but offering a much higher bending resistance. Furthermore, in the following section a new cable-supported system is supplemented to the designed longitudinals to provide a solution for the offset problem mentioned.

### A NEW DESIGNED LONGITUDINAL MEMBER

The new concept is based on the design philosophy that an optimal longitudinal member must be functionally decomposed into two separate systems: the first, called the crushing part, guarantees the desired stable and efficient energy absorption. The other, called the supporting part, guarantees the desired stiffness in the transverse direction, see Figure 1. This latter part is necessary to allow enough energy absorption during an off-axis collision and to give enough support with a sliding wall to protect the crushing part against a bending collapse.

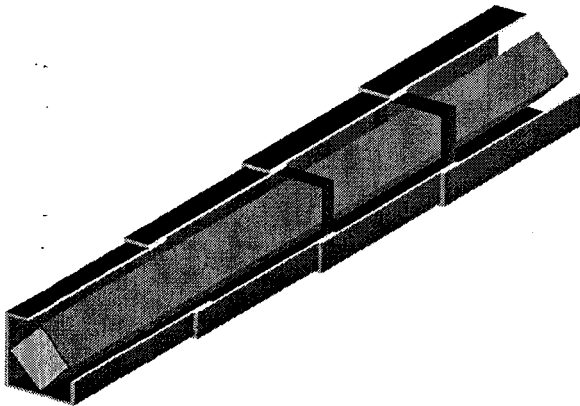
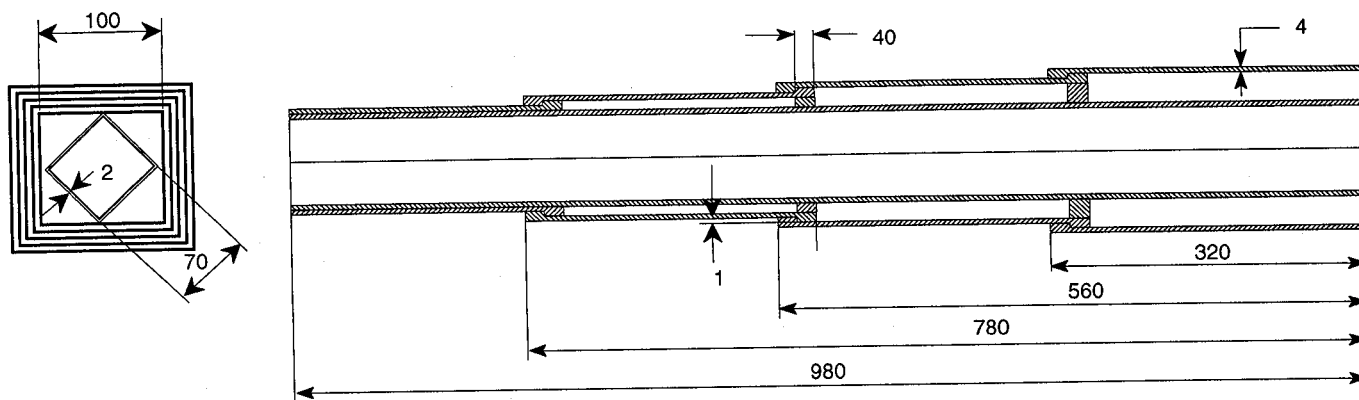


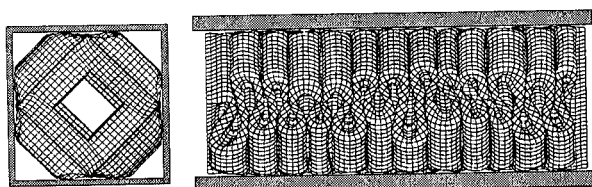
Figure 1. Interior view of the longitudinal member.

A square profile is chosen for the crushing part with a width of 70 mm outside and a thickness of 2 mm (Wittman 1995). The width dimensions of the crushing part are limited, as it has to fit within the available interior dimensions of the supporting part, depending on the available space between the engine and wheel envelope. The dimensions are based on a popular compact class car. The total length is 980 mm. The supporting part consists of four very stiff square profiles that fit into each other and may slide each over the other, like a telescope. Flanges prevent the telescope from falling apart. The overlap of the four supporting parts is maximized to 80 mm, this yields a high bending resistance and the supporting parts slide well into each other. Two supporting squared rings are necessary to prevent a bending collapse of the crushing part in the larger rear parts of the telescope. The same length of 980 mm can be shortened to 320 mm. To achieve a maximum deformation length, while taking into account the two supporting rings, the length of the supporting profiles must be from bumper to fire wall side successively: 280 mm, 300 mm, 320 mm and 320 mm. In this case, the available deformation length is 660 mm, 67.3 per cent of the original length. This must be enough for a compact class car. The maximal theoretical effective deformation is about 72.5 per cent of the length not deformed (Wierzbicki). Note that due to the presence of the rigid engine, in most collision situations the residual length of the longitudinal could not be less than the engine length. See Figure 2 for more details. The space between the corners of the crushing part and the inside of the supporting part is only 0.5 mm. At both ends of the longitudinal member, the two functional components are joined with a rigid plate.



**Figure 2. Drawing of the longitudinal member.**

The unusual angular orientation of the crushing part along the longitudinal axis of  $45^\circ$  with respect to the orientation of the enveloping support part has several advantages. At its corners the crushing part is supported by the enveloping square. No material deforms to the outside at the corners, which implies that at this position contact with the supporting part does not disturb the folding process. The narrow position of the crushing part in the enveloping supporting part gives a continuous sliding force as a support against bending. Note that during the deformation process the first part of the supporting structure with the smallest inner dimensions slides together with the folding front to the rear. After full deformation all the folds are packaged in the first supporting part. Figure 3 shows the lobes of the crushing part inside the supporting part after deformation.



**Figure 3. Crushing part inside the boundaries of the supporting part after deformation.**

The space needed for undisturbed folding is always guaranteed. The width growth of this preferred asymmetric fold (Witteman 1994) is nearly half of the not deformed width. This extra needed space is available due to the rotated orientation within the enveloping square.

The result is a longitudinal member with a conventional stiffness for stable energy absorption during a full overlap crash. It also has an extremely high bending resistance to absorb also energy during an offset or off-axis

collision, because a transverse load component can be transferred to an axial load.

Nevertheless, it is better to reach the same amount of energy absorption in the case of an offset crash as in a full overlap crash. Although this can be reached by further increasing the wall thickness of the supporting part, it is impossible to maintain an acceptable mass for the entire structure. Energy absorption by bending is very inefficient. A considerable amount of energy absorption is only possible with heavy structures. The only way to reach the same energy absorption and deformation length for an offset crash compared to a full overlap crash is to force the unloaded longitudinal to crumple as well, by means of a stable axial folding process. This is not possible with a very rigid transverse structure in the front. Bending moments will be introduced that are always too high. Also, the engine between the longitudinals reduces the possible shortening after a rigid transverse beam in front of the engine hits the engine.

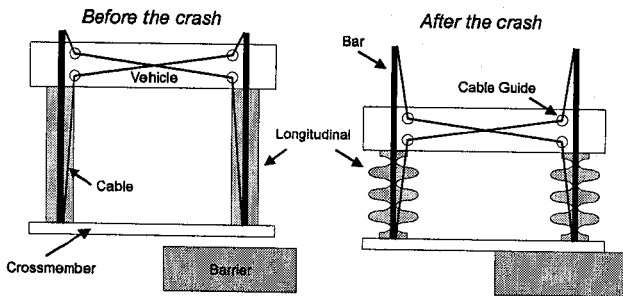
An interesting solution is the addition of two cables and two bars to the designed longitudinals. This new design idea will be introduced in the next section (see Figure 4). This cable connection will force the unloaded longitudinal of an offset crash to perform axial shortening with a tensile force to the rear.

### THE CABLE CONNECTION SYSTEM FOR A SYMMETRIC FORCE DISTRIBUTION

In Figure 4 a schematic sketch of a cable-supported frontal car structure is given. The system consists of two bars, two cables and four cable guides. The stiff bars are placed within the longitudinal members. At the front of the vehicle, they are connected with the cross member. The bars are longer than the longitudinals and extend beyond the vehicle's firewall. A cable is connected to the end of



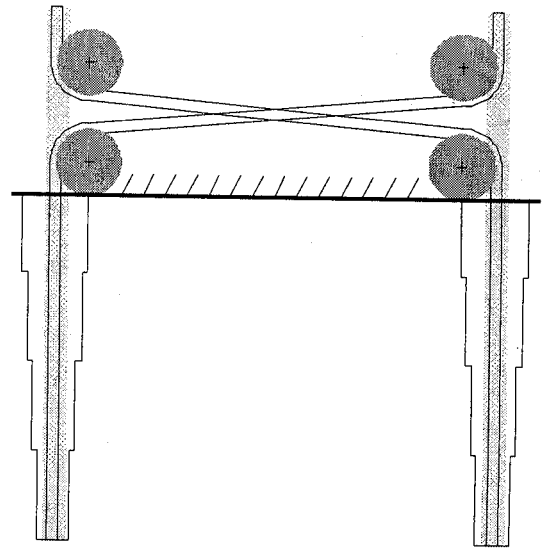
each bar. This cable is guided to the front end of the other longitudinal via two cable guides, where it is connected to the cross member. The working principle is rather simple: if one longitudinal is loaded and starts deforming, the bar moves backwards and pulls the cable, which leads the crushing force via the cable guides directly to the other, unloaded, longitudinal. The transmission of force is without loss of energy. Note that if both longitudinals are loaded (full overlap crash), the cable construction has no influence on the crash behavior.



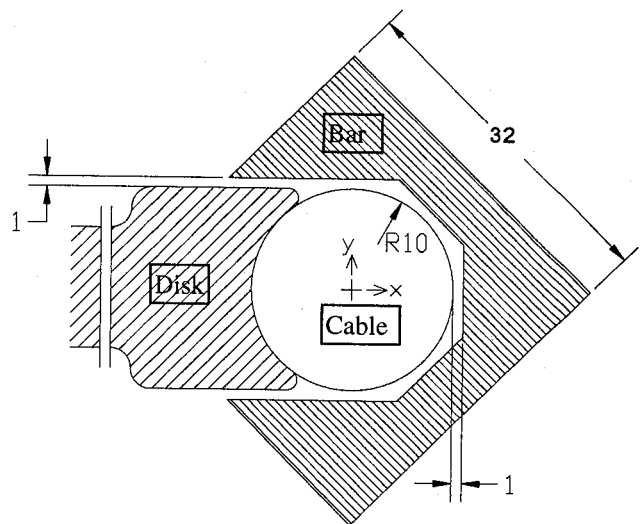
**Figure 4.** Principle sketch of a cable-supported longitudinal structure.

This cable concept could be built into all cars with conventional frontal structures. However, the novel design concept described offers two important advantages, which make it very suitable for combination with the cable construction. The bars need to have sufficient space to move back-wards. Because intrusion of the passenger compartment is not desirable, the bars must move under the vehicle. This means that the longitudinal members need to be positioned under a slight angle (higher on the bumper side, lower on the firewall side), due to the prescribed compulsory height at which the forces must be led into the structure. The first advantage is that the novel design concept is well suited to be positioned under an angle. Its high bending resistance guarantees that the structure will not collapse in a premature bending collapse, unlike most conventional longitudinal members. Second, the new design concept guarantees stable folding of the crushing part under all circumstances. Most conventional longitudinals have all kinds of connections with other parts under the bonnet, which can easily disturb the folding process. A stable folding process is necessary, because the bar is placed within the crushing longitudinal and should always be free to move back-wards. (Unstable folding would prevent the bar from sliding within the narrow space of the crushing profile. This would cause the cable system to stop working correctly). To avoid any

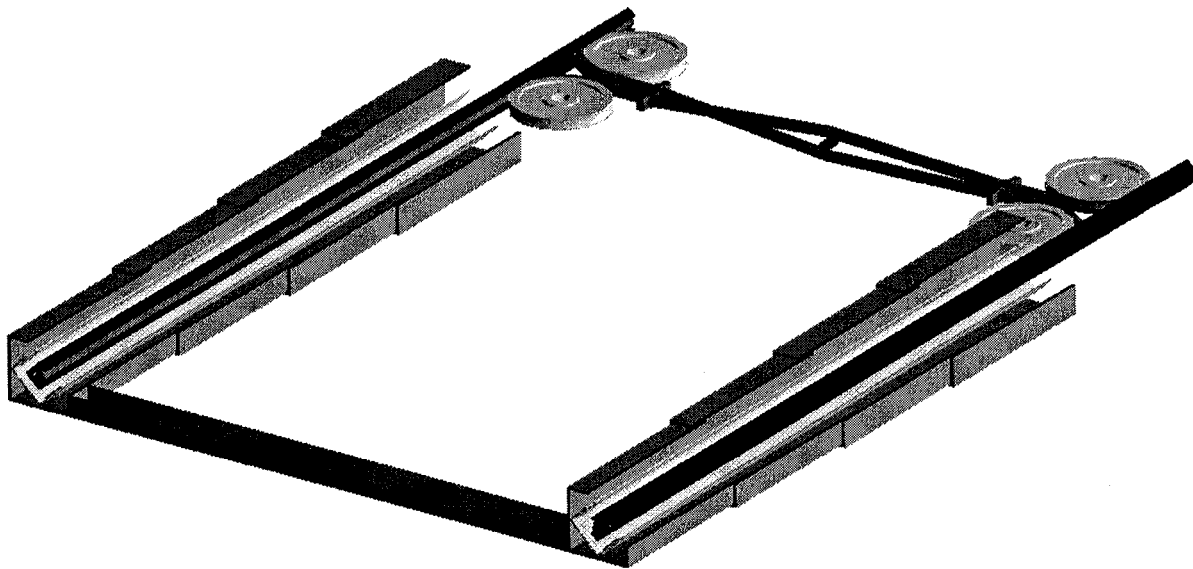
transverse forces on the sliding bar, the cable is guided through the center of the bar. This is possible if the two bars are formed like a U-profile and the cable guides fit into these U-bars. See Figures 5 and 6 for more details.



**Figure 5.** Top view of the cable-supported longitudinal structure.



**Figure 6.** Cross-section of the cable around the cable guide disk inside the bar.



**Figure 7. 3D open view of the cable-supported longitudinal structure.**

A steel 8-string wire-rope cable with a diameter of 20 mm has a fracture force of 279 kN. That means that a force up to 167 kN does not deform the cable plastically. Simulations (Slaats 1996) showed that in a real offset crash the peak load is below this value.

The free space inside the stable asymmetric deformed square crushing part is decreased to about half the original width. This was confirmed by simulations and experiments in our laboratory and done by others (Beermann 1982). This 50 per cent decrease means that the inner dimension of the square crushing part after forming folds will be nearly 33 mm. To prevent each disturbance of the regular folding process, and to guarantee enough sliding space, an outside width of 32 mm of the square sliding bar is chosen.

The cable guide disk has a minimized height of 20 mm, the same as the cable diameter. This is important because the bar must not be weakened more than necessary.

The buckling load of the bar was calculated to be 239 kN. This is also more than the expected peak load during a crash. For the buckling load, the free length of the bar is the same as the longitudinal length. Behind the firewall extra leading support for the sliding bar is necessary to ensure that movement only occurs in the axial crush direction. During the crash, the free buckling length decreases by additional support from the formed folds.

In Figure 7, the assembly of the new design concept with the cable connection system can be seen. In addition, extra cable guide rings preventing the cable from slipping off the disk and a pin mounted to the firewall at the

crossing point of the cables are showed. Note that the center lines of the cable, bar and longitudinal fall together yielding axial forces only. The position of this cable-supported structure built inside a car is under a slight angle, therefore the two bars can move freely to the rear under the car floor during a crash.

### **BUILDING THE LONGITUDINAL STRUCTURE IN A NUMERIC FRONTAL CAR MODEL**

Since a simulation has shown that the principle of the cable support works without disturbing the regular folding process of the longitudinals (Witteaman 1996), a complete frontal car model is useful for evaluating more realistic crash situations. Just in case of an offset or an oblique crash situation, it is important that the model can move realistically. In a realistic test procedure, a vehicle moves freely with a velocity against a rigid stationary obstacle. Due to asymmetric forces during offset or oblique collisions, the back of the vehicle could turn a little, which implies an extra bending moment on the longitudinals. In addition, the mass inertia of the structure has an influence on the crash behavior. Especially the bars inside the longitudinals are stopped abruptly.

The longitudinals are responsible for the largest part of the energy absorption, for the necessary repeating folding process it is important that there is a good load introduction in axial direction. In case of a 30 degrees collision against a rigid barrier, the stiff corner of the first supporting part in front of the longitudinal will generate a bending moment, which can cause a bending collapse. To

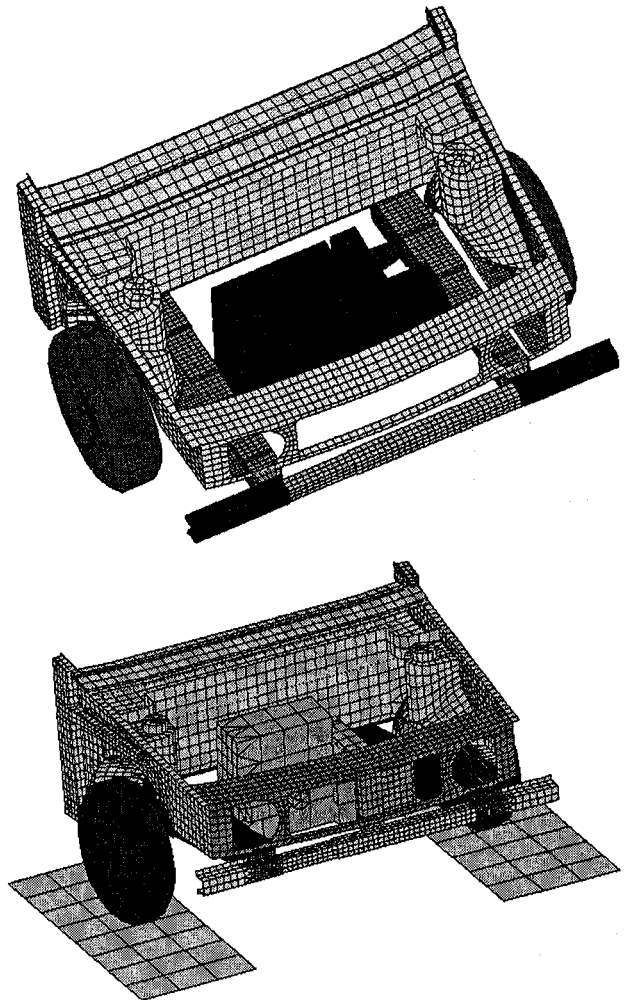
avoid this rotation, the front of the first profile is changed into a flattened top of 60 degrees. This top can also provide the connection between the support profiles and the bumper. The top deforms in such a way that the moment applied on the first profile will be reduced. The bar inside the crushing part, which has a rigid connection with the stiff supporting part, has in case of a deformable top a less abrupt deceleration during the impact. This is important to prevent a buckling caused by its own inertia.

The frontal model should contain the most important structural parts that influence the way of energy absorption. The aim is to avoid deformation of the passenger compartment; all the crash energy must be absorbed by the total front structure. This implies that the frontal model boundary starts at the deformable firewall, which is connected to a not deformable cage. Rigid nodes on the wall borders, which also contain a part of the mass distribution of the not modeled vehicle side, can simulate this cage. In front of the cage the following deformable and rigid components are necessary, see Table 1.

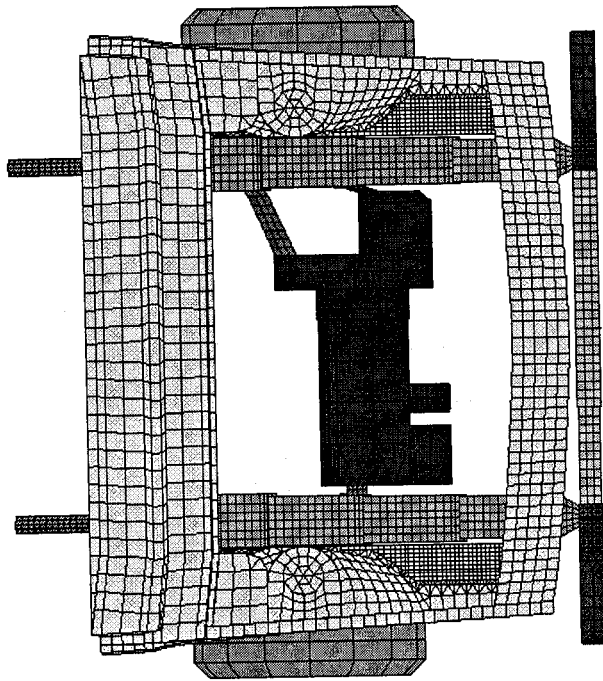
**Table 1.**  
**Important frontal vehicle components**

component	deformable body	rigid body
fire wall	✓	
longitudinals	✓	
bumper	✓	
bumper stay	✓	
lateral wing	✓	
lateral wing reinforcement	✓	
front panel	✓	
engine mountings	✓	
engine and gearbox		✓
front wheel suspension		✓
front wheel rim		✓
front wheel tire		✓

For the simulation of a crash, also the surroundings like the ground plane and an obstacle should be modeled as rigid body. Although the rigid bodies in the front model do not absorb energy by deformation, their masses represent by the initial velocity an amount of energy. The rigid volumes influence the available space and order for movement of the deformable parts and their own movement could deform the surrounding deformable structures. See Figures 8 and 9 for the complete model.

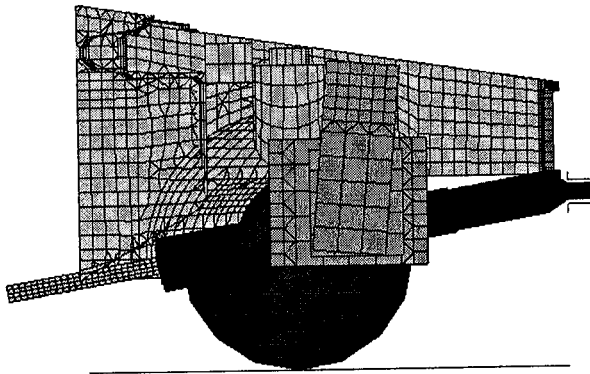


**Figure 8.** 3D views of the complete frontal vehicle model.

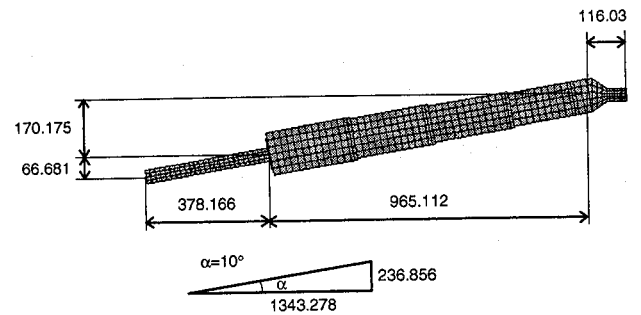


**Figure 9. Top view of the complete frontal vehicle model.**

More details of the longitudinal positioning with an angle of 10 degrees with the horizontal plane are showed in Figures 10 and 11.



**Figure 10. Cross-section of the frontal vehicle model.**



**Figure 11. Dimensions of the compact class longitudinal in mm.**

The design of the engine mountings has an important influence on the crash behavior of the structure it is connected to. Because the longitudinal members are a relatively stiff body part and therefore ideally for connecting heavy components, they are often used to carry the engine. However, if the rigid engine block is mounted with two points to the longitudinal, the part between the mountings is bridged and can not deform as programmed. In addition, in case of one mounting point, the rigid connection of the engine with the drive line will bridge the longitudinal as well with a rigid link. This is more critical with the mounting point more in front of the car. Otherwise, if the mounting points are positioned opposite to each other on both longitudinals, it gives a rigid support against bending in case of asymmetric loads.

To connect the engine on the outside of the supporting parts, it must be fit at the front of the fourth profile at the firewall. Because the engine geometry requires a second mounting point on the same longitudinal, it can be fitted on the front of the third profile. Because the first (rear) mounting point is a deformable beam which collapses during a crash, the third profile can slide inside the fixed fourth profile while deforming the mounting. In this way, the first two profiles can slide into the third profile during the first part of the crash where the engine is not directly involved. During the second part of the crash the engine moves backward together with the movement of the third profile into the fourth profile, yielding a normal deformation length. Figure 12 shows the principle working of the engine mounting in four simulation steps. Note it is a top view with the longitudinal rotated finally more as 10 degrees.

To investigate the vehicle's deformation and its influence on the longitudinals with support and cable system, different frontal crashes are simulated in the next sections.

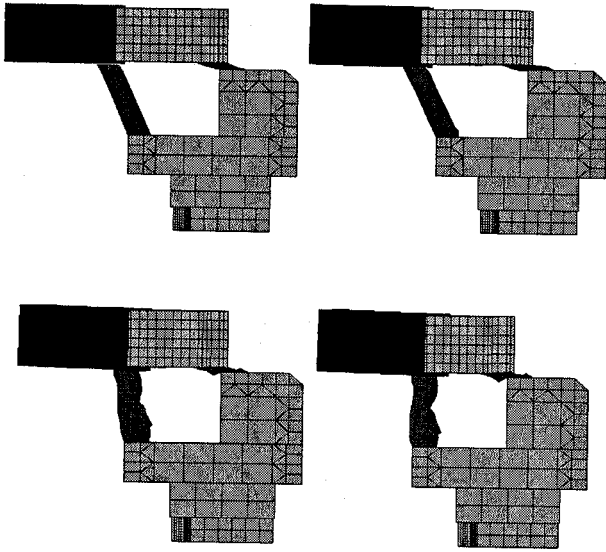


Figure 12. Deformation of engine mountings.

#### NUMERICAL SIMULATION OF A FULL OVERLAP CRASH

The following numerical simulations are performed with the complete frontal vehicle model, with the cable supported new design concept built in a compact class vehicle front structure. The total mass is 1053 kg, the crash velocity of the car is 56 km/h and an infinite friction between the vehicle model and the rigid barrier is prescribed.

In the full overlap crash against a rigid wall, the cable system has no function. Both longitudinals are loaded directly with an axial force direction. However, the cables and bars might not disturb the folding process. Both bars should slide backwards without pulling the cables. In Figure 13 six simulation steps are showed. In this top view the front panel is only shown for  $t=0$  ms to have a better view on the deformation of both longitudinals and the engine.

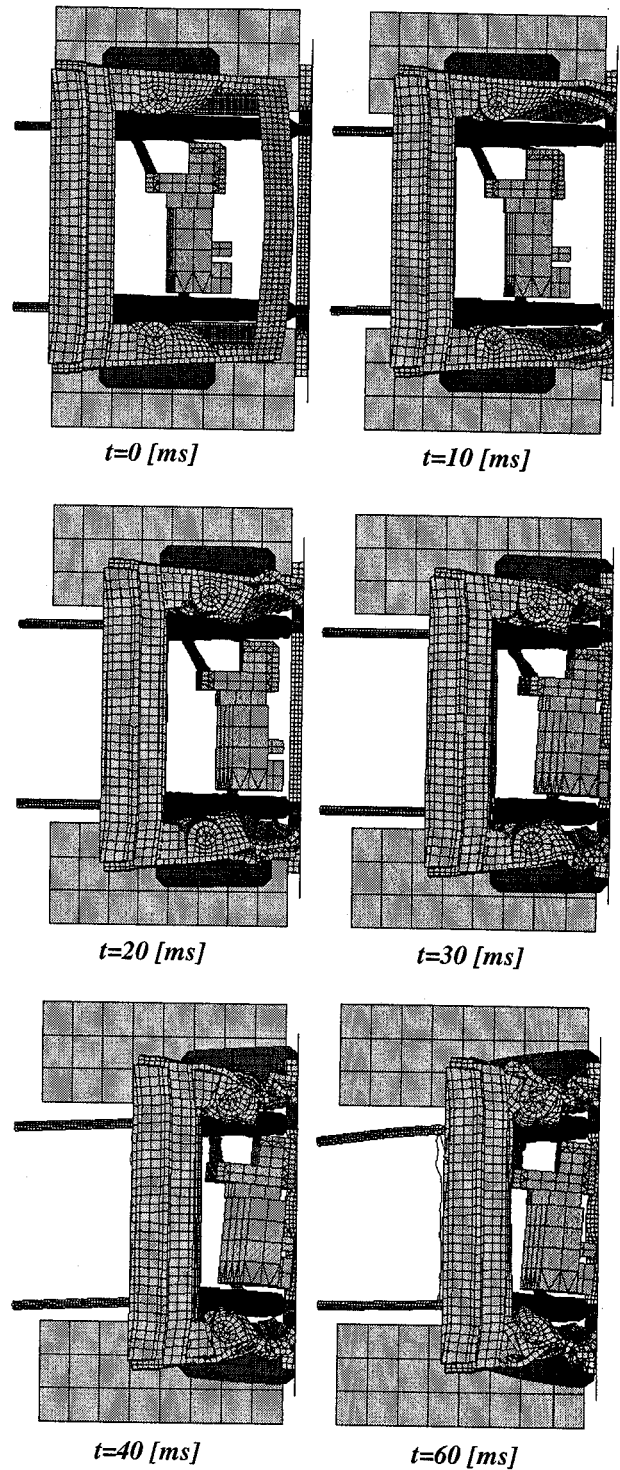
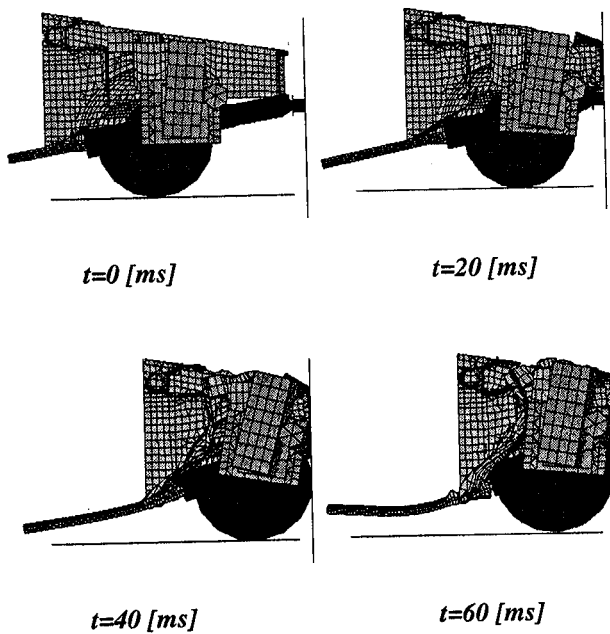
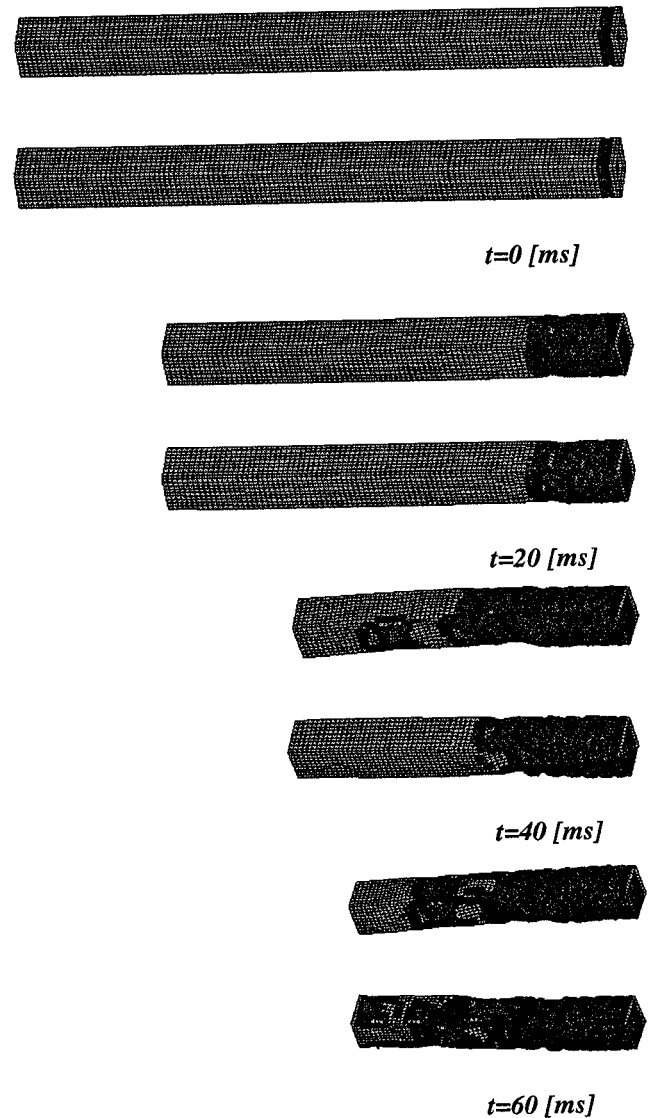


Figure 13. Top view of a full overlap crash (56 km/h) in six time steps.

In Figure 14, a side view of the vehicle deformation is showed in four time steps. It can be seen that the position angle of the longitudinal increases during the crash starting from 10 degrees. In both figures it is also clear that the bars can freely move backwards, the cables are not tighten and both longitudinals have an equal deformation behavior. In Figure 15 the regular folding patterns of the crushing parts inside the telescopes are viewed. In the undeformed state, the modeled triggering can be seen. This little fold ensures that the folding process starts at the front side without a too high peak force. At  $t=40$  ms a little extra deformation can be found due to the collision of the engine with the left supporting part.

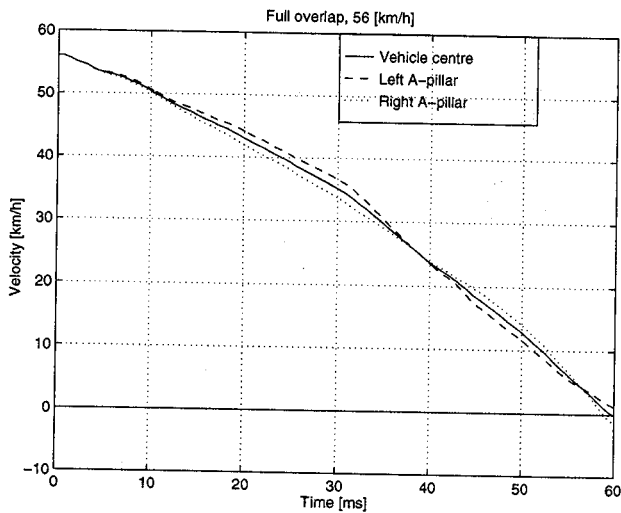


**Figure 14.** Side view of a full overlap crash in four time steps.

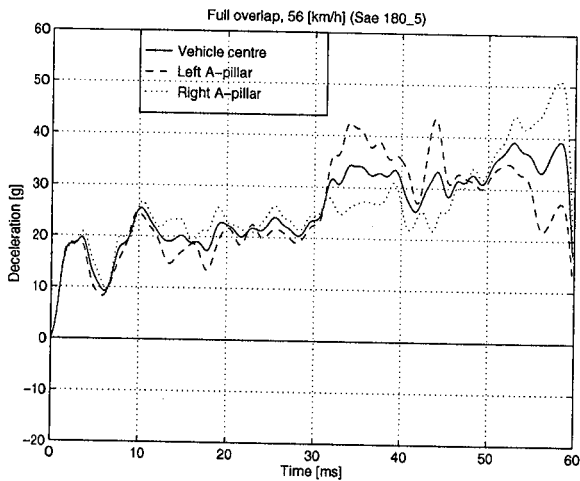


**Figure 15.** Inside view, folding process of both crushing parts in four time steps.

The calculations are ran until 60 ms and at that moment, the velocity is reduced to 0 km/h. This is showed in Figure 16. The division of the weight of the engine mainly causes the little difference between the movement of the left and right A-pillar. The more accurate mesh of the left engine side results in more nodes with additional masses. The same effect can be seen in Figure 17 in which the deceleration level is plotted. During the first part of the crash, the deceleration of the vehicle model is about 20 g. After  $t=30$  ms the engine encounters the rigid barrier causing the vehicle to decelerate up to about 35 g.

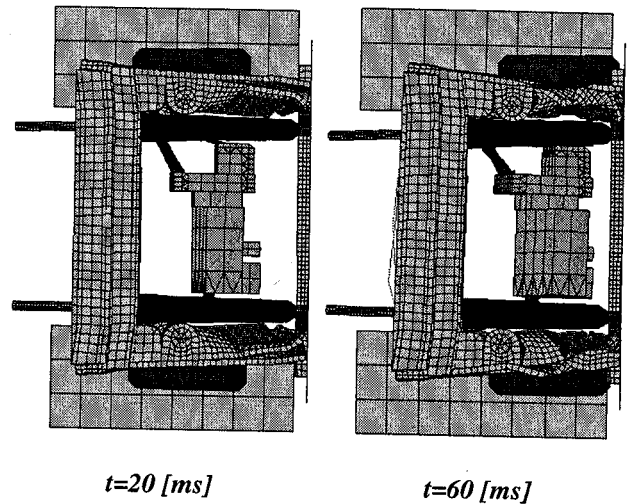


**Figure 16.** Velocities of a full overlap crash with 56 km/h.

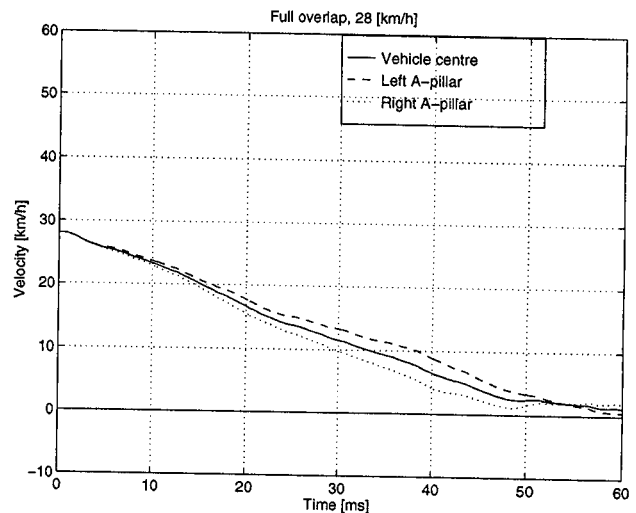


**Figure 17.** Decelerations of a full overlap crash with 56 km/h.

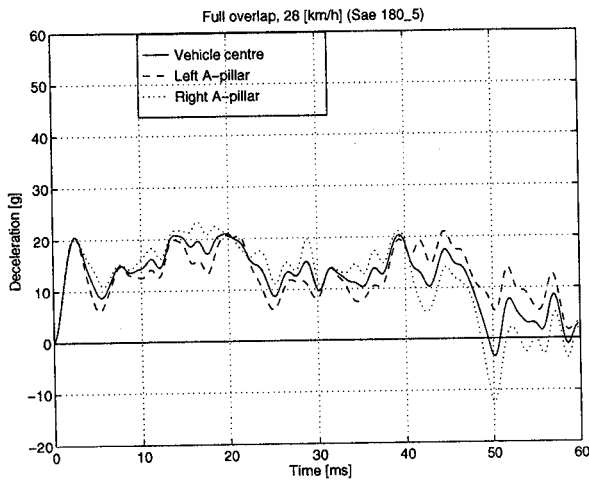
To see the influence of the crash speed on the resulting decelerations of the vehicle model, the same simulation is done with 28 km/h. In this case, the engine is not involved. In Figure 18 two interesting time steps in top view are showed. In Figure 19 and Figure 20 the velocities and decelerations are plotted. The crash time is in both crashes about 60 ms. The deceleration of the 28 km/h crash is lower, it fluctuates between 10 g and 20 g until it further drops after 45 ms.



**Figure 18.** Top view of a full overlap crash (28 km/h) in two time steps.

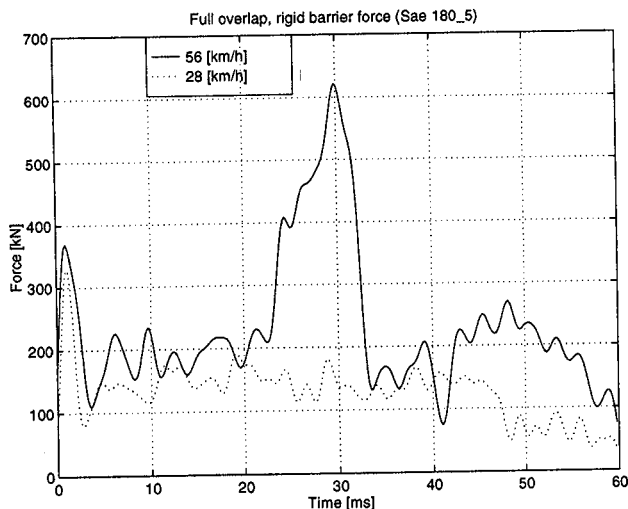


**Figure 19.** Velocities of a full overlap crash with 28 km/h.



**Figure 20. Decelerations of a full overlap crash with 28 km/h.**

In Figure 21, the rigid barrier force is plotted of both full overlap crashes. The traditional first force peak to start the folding process can be seen in both crashes. In addition, the peak of the 56 km/h crash on 30 ms where the engine hits the barrier can be recognized.



**Figure 21. Rigid barrier forces of a full overlap crash at 56 and 28 km/h.**

## NUMERICAL SIMULATION OF A 40 PER CENT OFFSET CRASH

The vehicle model is impacted with an initial velocity of 56 km/h against a rigid barrier with infinite friction. Although using a deformable barrier will result in more

realistic deformations for a car to car collision, use is made of a rigid barrier with regard to the computation time. With the rigid barrier, it is also possible to evaluate the working principle of the new design with cable system.

For a well functioning of the cable system, it is important that there is a rigid side support of the gliding bars behind the longitudinals. This has an important influence on the Euler buckling load of the cable bar. If the bar collapses, it could not tighten the cable of the unloaded longitudinal. This collapse load is 239 kN, without a slide contact, this maximum load will be only half. In the physical design the cable guide disks and a stiff bar leading profile connected with the vehicle floor could perform this function. In the numeric model, the cable guide disks are substituted by slip rings. For the necessary side support, additional rigid planes are modeled.

To ensure the forces on the cable bar should be kept lower as the calculated buckling load, it is important that the load which stops the bar from moving is not combined with the load necessary to start the folding process of the unloaded longitudinal. Simulations have shown (van Leeuwen 1997) that the impact from a single bar against the rigid barrier generates a force with a maximum of 150 kN. The initial load to start the folding process can be estimated from the full overlap crash. In Figure 21, the maximal rigid barrier force at the start is about 360 kN. This peak value is the result of the traditional peak force of forming the first fold in both longitudinals. This means that in order to deform each side of the vehicle, for one side the necessary peak load will be maximally about 180 kN. Both values are safe below the buckling load of 239 kN. To separate these loads, the cable length is elongated by 30 mm. After the loaded longitudinal bar is stopped, and the first fold is formed, the cable is tighten and starts deforming the unloaded side. With these model adjustments numerical simulations are performed, see Figure 22 for a top view of the deformation in six time steps. Again the front panel is only shown at  $t=0$  ms.



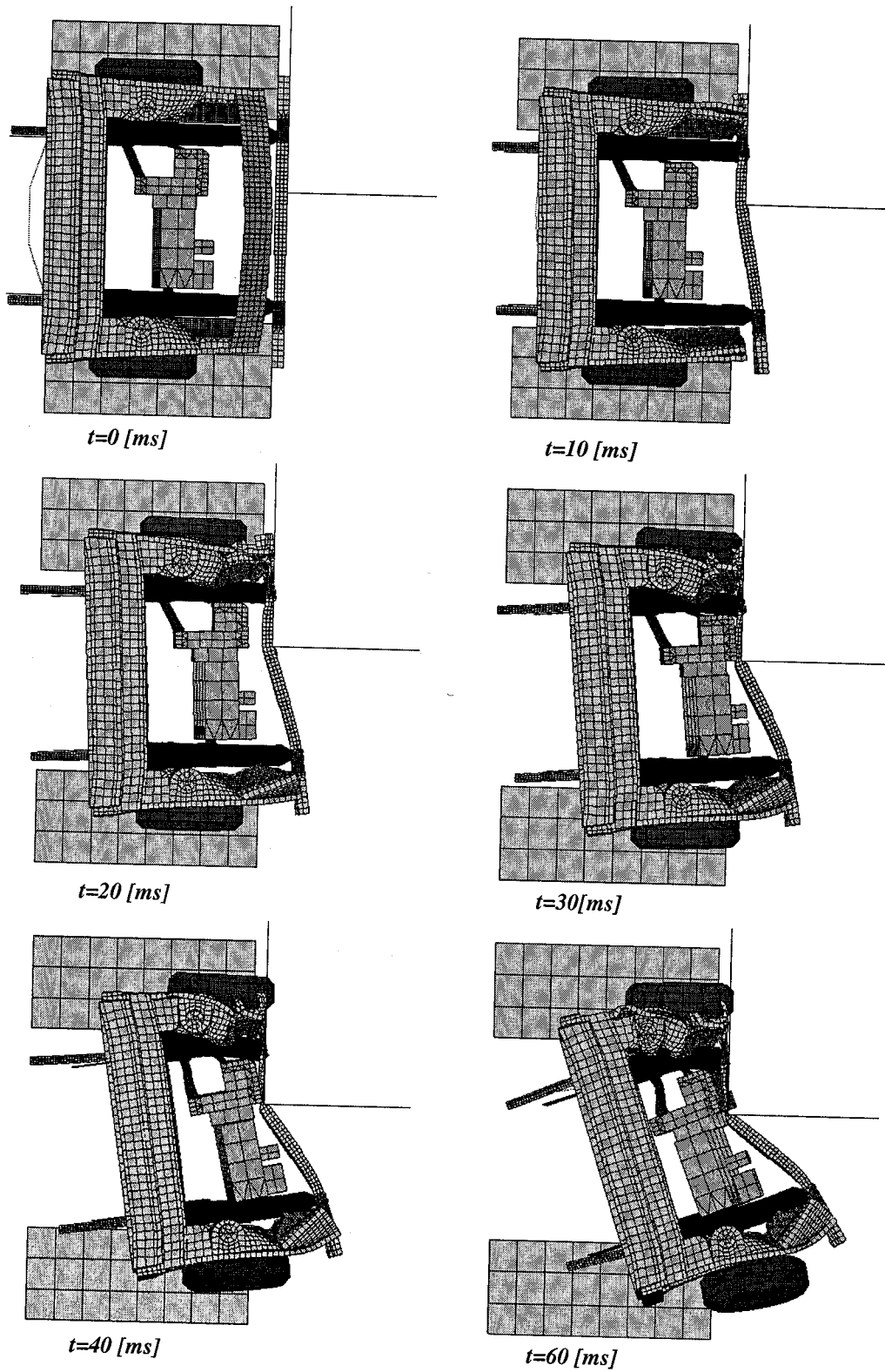
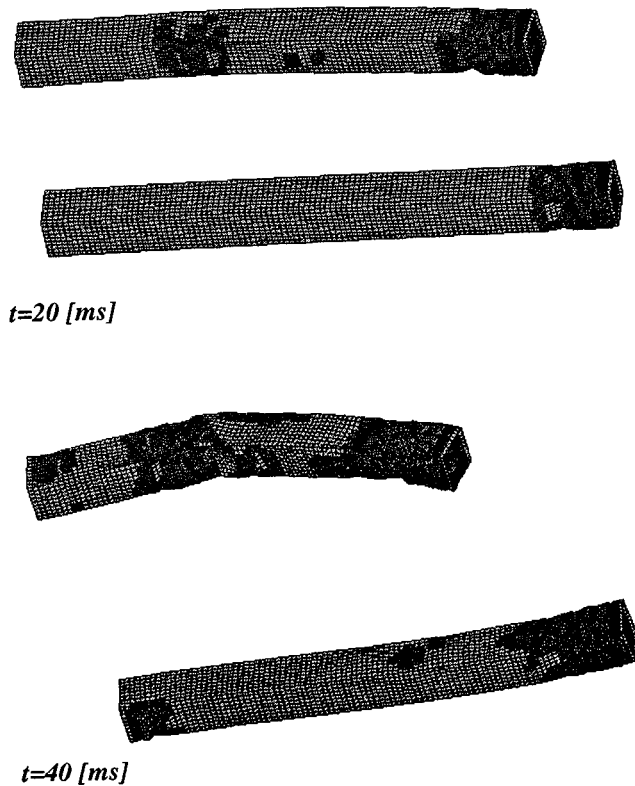


Figure 22. Top view of a 40 per cent offset crash in six time steps.

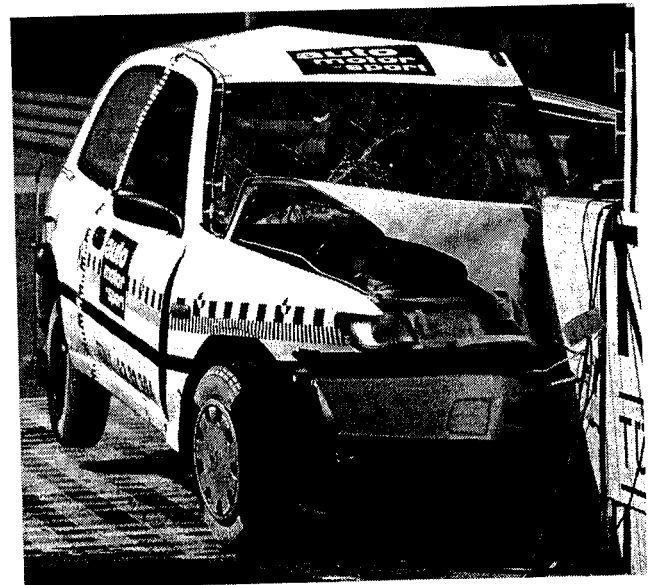
From these figures, it can be concluded that the cable system is working in principle. The unloaded vehicle side is also deformed, and both bars slide backwards. The unloaded longitudinal collapses in a folding mode and during the first stages (until 20 ms) of the impact both longitudinal members show a stable folding process. See Figure 23 in which the folding process of the crushing parts is visualized. It can be seen that after the first fold is formed in the loaded longitudinal, the unloaded longitudinal starts forming folds. However, after 20 ms the folding process in the loaded longitudinal is disturbed and it will collapse in a bending mode. Although the bar inside the longitudinal starts to bend after 20 ms, it is still pulling the cable resulting in continuing of the folding process in the unloaded longitudinal until about 40 ms.



**Figure 23.** Inside view, folding process of both crushing parts during an offset crash in two time steps.

One important reason for this undesirable distortion of the loaded longitudinal is a limitation of the numeric model. Normally, a complete vehicle on four wheels with a normal mass distribution (e.g. and luggage in the back) crashes against the barrier. In this simulation, the masses

of the not modeled parts are distributed on the modeled front parts as the firewall, the wheels, wing and reinforcement, and the longitudinals. However, this leads to an unrealistic rotation of the heavy vehicle front around the rigid barrier. Due to this rotation the loaded longitudinal, which has a stiff connection with the bumper which fits to the barrier, has to bent because the backside is not fixed and moves sideways. A real vehicle has a much higher mass inertia due to the longer distance from the impact point to the center of gravity. This means it takes a longer time with a higher force level to rotate the vehicle. This can be proved with photos of real crashes, in which the vehicle does not rotate during the crash, despite the cars mostly lift up the back wheels. See Figure 24 in which an offset crash with 55 km/h against a rigid barrier is showed with a comparable compact class car. The alignment until the end of the crash with the floor squares is striking.

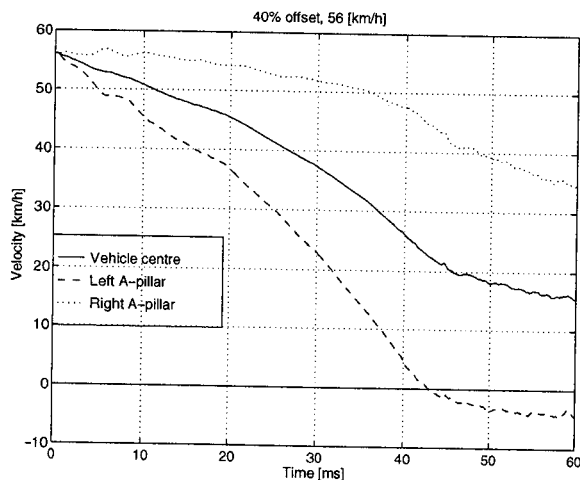


**Figure 24.** Example of an offset crash with no vehicle rotation. (AMS magazine)

A possibility to model this mass deviation more realistically in future is by means of a centralized mass behind the firewall connected with beams. A more usable solution will be a not deformable cage (rigid bar elements) with a correct mass distribution (Landheer 1996) in which a finite element dummy can be placed for injury research. In this case, most calculation time is spent to the vehicle parts that has to deform.

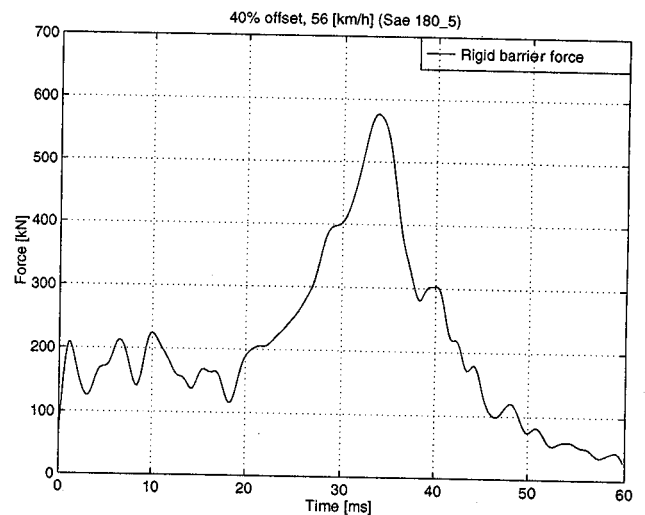
The extreme rotation of the vehicle also appears in the velocity curve of the vehicle front in which a large

difference arises between the velocity of the left and the right A-pillar. If the left side is stopped after 43 ms the unloaded right side still moves with 44 km/h. See Figure 25.



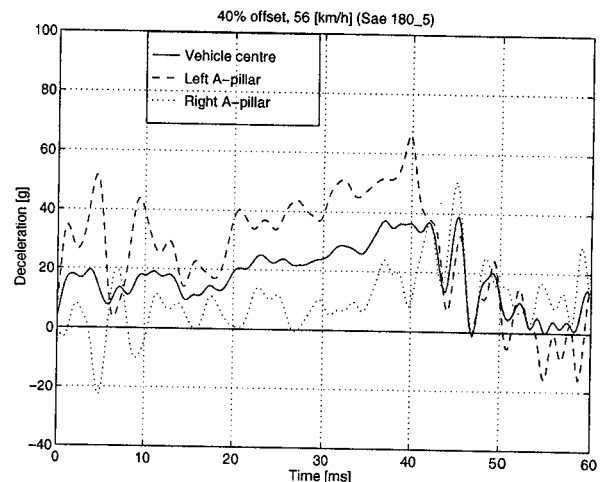
**Figure 25. Velocities of an offset crash.**

In Figure 26, the rigid barrier force is plotted. It is clear that the maximum load until the engine hits the barrier (after  $t=30$  ms, see also Figure 22) fluctuates below a safe level of 200 kN. After 23 ms the force increases due to deformation of the front by the engine. This load curve has much similarity with the rigid barrier force of the 56 km/h full overlap crash in Figure 21, except the higher starting peak due to two starting longitudinals simultaneously. However, this comparable load of 200 kN is in case of an offset crash not symmetrically on the vehicle front but asymmetric on one side. Thus, another reason for the extreme vehicle rotation is the fact that the offset load due to the cable system is much higher yielding a higher rotation force compared with a traditional vehicle front. Also the fact that at this moment the used longitudinal is axial a little too stiff for this particular compact class car, makes a rotation easier. If a longitudinal is too stiff, the vehicle is stopped with a higher deceleration as necessary and before the engine could hit the firewall, as is now the case. The vehicle now has reserves for more mass or a higher crash velocity.



**Figure 26. Rigid barrier force of an offset crash.**

The decelerations of the offset crash for the left and right A-pillar are showed in Figure 27. The same large differences as found in the velocity curves are found in this figure. In the first 43 ms, in which the left side decelerates to a halt with deceleration peaks of up to 60 g, the maximum deceleration on the right side is about 20 g.



**Figure 27. Decelerations of an offset crash.**

# NUMERICAL SIMULATION OF A 30 DEGREES CRASH

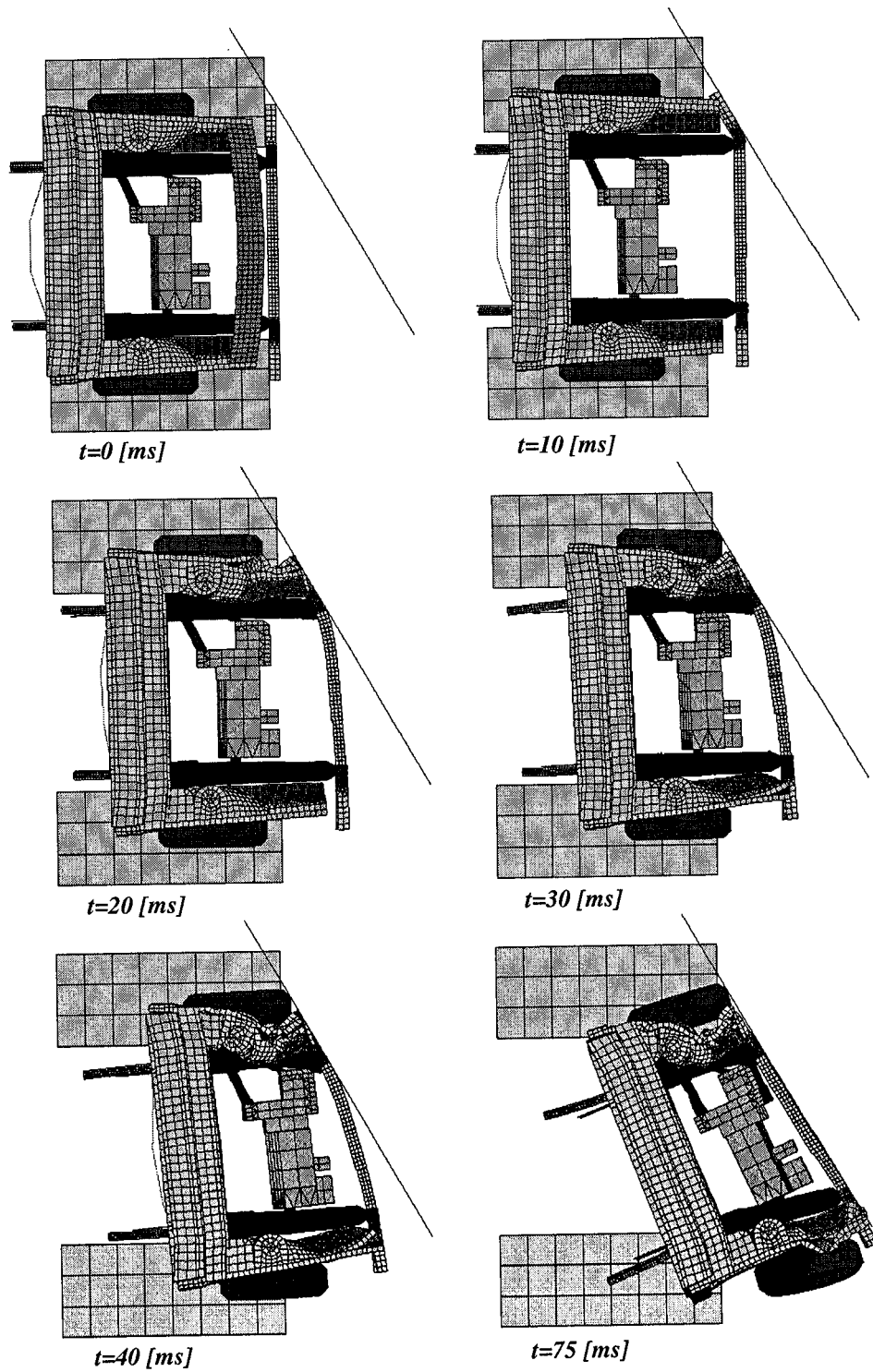
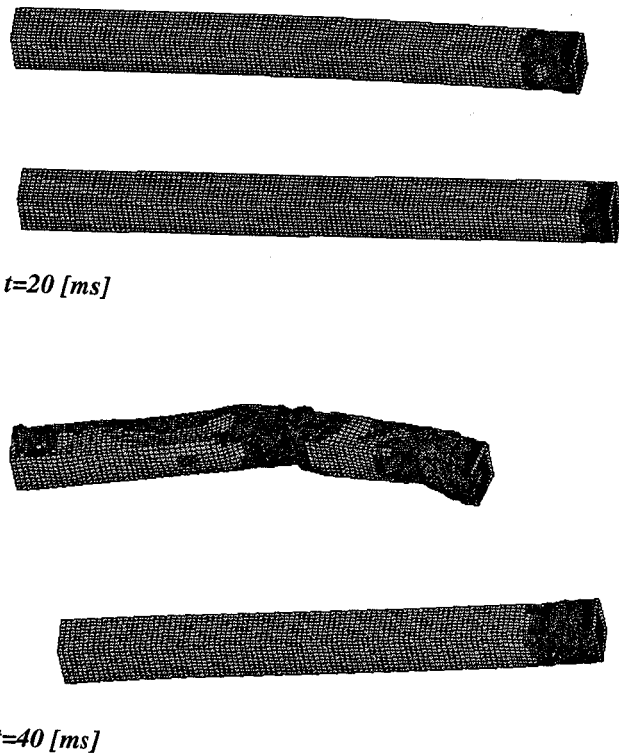


Figure 28. Top view of a 30 degrees crash in six time steps.

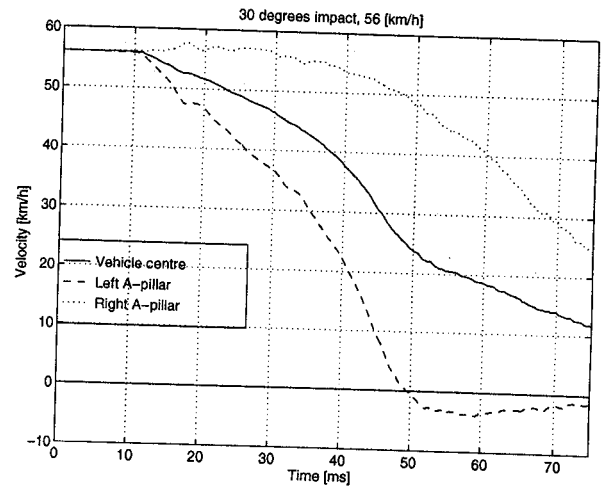
The same model adjustments as for the offset crash are necessary for a 30 degrees crash. In Figure 28, the top views of the deformation are showed in six time steps. Again the cable system is working until  $t=40$  ms. Note that the first 11 ms only the bumper deforms, after that time the longitudinal starts to deform. However, after 30 ms the loaded longitudinal starts to collapse, and after  $t=40$  ms the bar which pulls the cable does not move backwards anymore. This leads to the end of the folding process in the unloaded longitudinal. See also Figure 29 in which the folding process of the crushing parts is visualized. At  $t=40$  ms the engine is crushed against the left longitudinal. More folds are formed after the unloaded longitudinal encounters the rigid barrier after 60 ms. As can be seen in Figure 28 on stage  $t=75$  ms, the unloaded longitudinal has not bent and is still able to form folds.



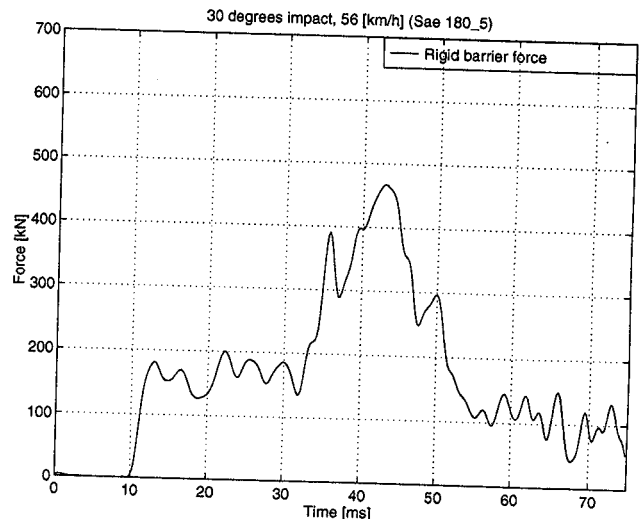
**Figure 29.** Inside view, folding process of both crushing parts during a 30 degrees crash in two time steps.

The velocity curve of the 30 degrees crash is plotted in Figure 30. The large difference in velocity between the left and right A-pillar again indicates the vehicle rotation.

At  $t=75$  ms the right side of the vehicle has still a velocity of 25 km/h, which can be further reduced by the right longitudinal, while the left side has absorbed enough energy to stop at  $t=49$  ms.



**Figure 30.** Velocities of a 30 degrees crash.



**Figure 31.** Rigid barrier force of a 30 degrees crash.

The rigid barrier force is plotted in Figure 31. In the first 10 ms, it is very low because only the bumper collapses. After 33 ms the engine is crushed increasingly more against the bending longitudinal in front of the engine, this generates a force peak to decelerate the engine. From  $t=57$  ms to the end of the crash the right longitudinal is making more folds, as can be seen by the

fluctuating force level. This fluctuating level is lower as in the first stage in which both longitudinals form folds.

It is obvious that the rotating of the vehicle resulting in the velocity difference on both sides also has its influence on the decelerations. The same difference between both sides is found. At the beginning of the crash of the loaded longitudinal, the unloaded side is accelerated a little bit, see the negative deceleration in Figure 32.

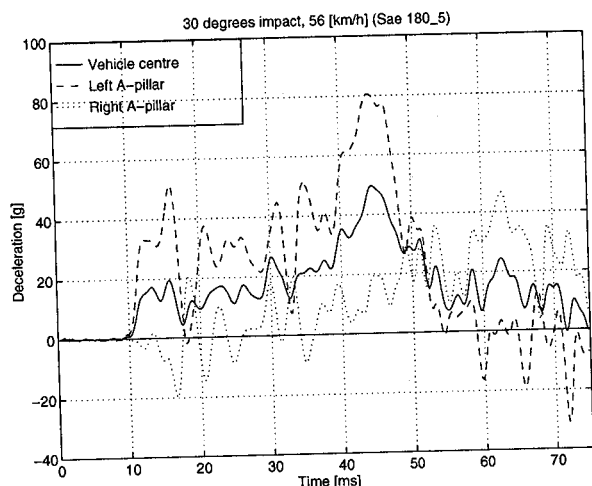


Figure 32. Decelerations of a 30 degrees crash.

## CONCLUSIONS

A structure consisting of two stiff sliding bars and two cables connecting the rear of one bar inside one longitudinal to the front of the other longitudinal is added to the new design concept to transmit the crushing force from the loaded to the unloaded longitudinal. Numerical simulations with a complete frontal vehicle model showed that both longitudinals have a stable folding pattern during the first half of an offset or a 30 degrees crash. In the second half of the crash, the vehicle rotates too much which creates a bending in the loaded longitudinal. Model modifications like a better mass distribution (yielding correct inertia properties) and a less stiff crushing part could prevent this problem in future. In addition, some numeric problems between the cable and the gliding bar resulting in unrealistic deformation of the bar and the crushing part should be solved. The bar collapses after 40 ms. This can also be seen in Figure 14 at stage  $t=60$  ms where the bar has not a straight form in side view. A too simple modeling of the cable for minimizing the computation time causes this contact problem. By this reason, the total energy of the system increases after 40

ms, while it has to be constant. The kinetic energy of the model decreases as expected after 40 ms, which means that most simulation results are usable. The increasing total energy involve also the internal energy which means that the graphs of the absorbed energy in Figure 33 are not valid after 40 ms, note the abrupt increase at that point.

One of the objects of the cable system is to obtain the same energy absorption for all impact configurations, achieved by a stable folding process of both loaded and unloaded longitudinal. This should result in vehicle deformations and decelerations that are not excessively high. In Figure 33 the energy absorption of both longitudinals are presented for a full overlap, a 40 per cent offset and a 30 degrees impact with all 56 km/h. As a reference, also the energy absorption of the longitudinal in case of a 40 per cent offset without the cable system is shown.

As the longitudinal energy absorption is not accurate after 40 ms, in Figure 34 the energy absorption's are presented until 40 ms. In Figure 33, the impression could be made that there is less energy absorbed by the longitudinal deformation of the 30 degrees crash compared to the other collisions. However, the longitudinals are deformed later in time, as first the bumper has to deform before the longitudinals encounter the rigid barrier. Only after 11 ms the longitudinals start to deform. For a better comparison in Figure 34, this delay of longitudinal deformation is taken into account.

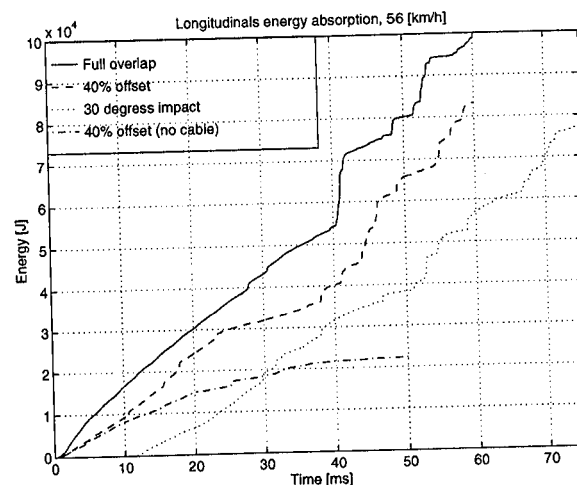
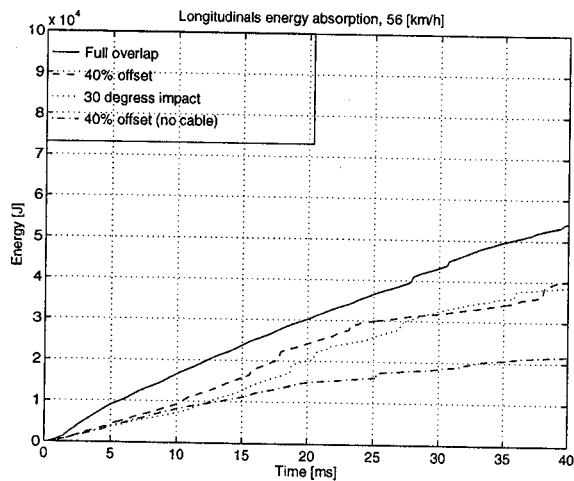


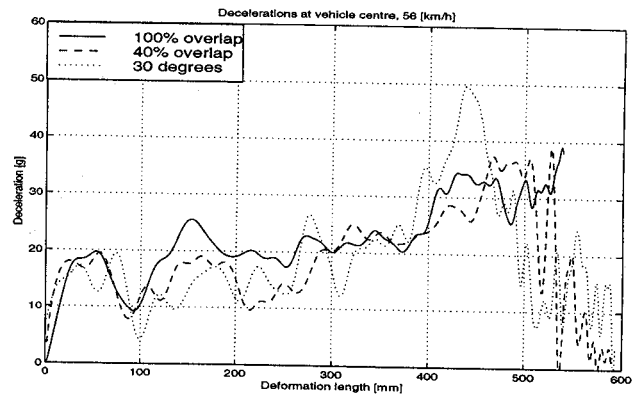
Figure 33. Total energy absorption of the longitudinals in different crashes.



**Figure 34. Energy absorption of the longitudinals in different crashes during 40 ms.**

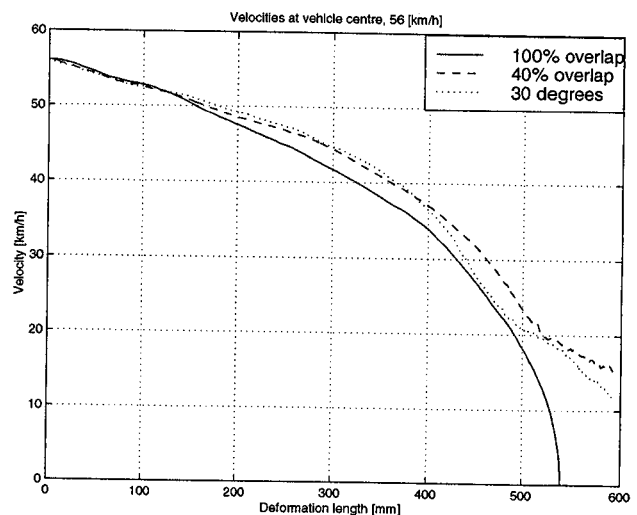
The conclusion can be drawn that using an advanced longitudinal design with cable system increases the energy absorption considerably in case of an offset and an oblique impact. However, the energy absorption is still less than the energy absorbed in a full overlap crash. For this difference, several reasons are mentioned. Another reason is of course the fact the unloaded longitudinal is loaded by the cable after the loaded longitudinal has formed one fold to prevent a peak load. It can be seen that the energy absorption's of the offset and oblique crash initially stay below the energy absorption of the full overlap and after a few ms the difference remains relative constant for a longer time.

In Figure 35 the already showed deceleration levels of the full overlap, 40 per cent offset and the 30 degrees collision are combined in one picture as function of the deformation length instead of the normally used time axis. Again for a better comparison with the 30 degrees collision, for this crash situation a time correction of 11 ms resulting in 171 mm displacement is taken into account. Until 480 mm deformation (about 40 ms) the deceleration levels are accurate, after that time numerical instability occurs as already mentioned.



**Figure 35. Comparison of the deceleration levels in three different crash situations.**

Although the shape of the deceleration curves is sometimes whimsical, in several deformation intervals the level is similar. Figure 36 shows a more uniform course where the velocities are plotted against the deformation length. There is not so much difference in velocity decrease between the complete different collision situations (excluding the inaccurate end).



**Figure 36. Comparison of the velocities in three different crash situations.**

Further optimization of the numeric model is time consuming and cost a lot of computer time. This is at this moment not considered because the simulation results will always show deviations with a real crash. Reason is that many unknown factors like the final engine geometry and possible position and other not modeled parts have an influence on the crash behavior of the longitudinals.

Otherwise, adjustments in the structure are necessary to reach a wished deceleration level, which also depends on the final weight of the car. Main goal for these simulations is to show the designed system could work and despite all limitations, the difference in energy absorption between the most important crashes is considerably reduced. This is a very important result, because with this advanced design the same deceleration level of the car could be reached for each crash overlap percentage. Now it is possible to design a frontal car structure with one optimal stiffness that hardly varies for different crash situations. Hence, one optimal occupant deceleration level yielding the lowest injury levels is obtained over the entire collision spectrum.

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# INJURY PATTERNS AMONG AIR BAG EQUIPPED VEHICLES

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## ABSTRACT

The University of Miami's William Lehman Injury Research Center at Jackson Memorial Medical Center conducts interdisciplinary investigations to study seriously injured restrained occupants in frontal automobile collisions. Engineering analysis of these crashes is conducted in conjunction with the National Crash Analysis Center at the George Washington University. The multidisciplinary research team includes expertise in crash investigation, crash reconstruction, computer graphics, biomechanics of injuries, crash data analysis, emergency trauma care, and all of the medical specialties associated with the Ryder Trauma Center at Jackson Memorial Hospital. The Lehman Center is a founding member of the newly created Crash Injury Research and Engineering Network referred to as "CIREN". More than 200 injured occupants and their crashes have been studied in depth.

By careful study of injured crash victims, their vehicles and the crash scene, injury patterns emerge. These patterns form the basis for hypotheses, which can be explored further by analysis of mass crash data, crash tests, and computer modeling. As a consequence, recommendations can be developed for injury control measures.

In the census of cases involving drivers protected by air bags in frontal impacts at the Lehman Center, heart injuries were present in about 9% of the cases, and liver injuries occurred in 19% of the cases. The chest/abdominal region accounted for 44% of the injury weighted harm. The chest comprised 68% and the abdomen 32% of this harm fraction. In examining the harm to the chest, the ribs and heart contributed about 43%. In examining the abdomen, the liver contributed 53% and the spleen 26%.

Liver injuries were most common in cars with right front damage, and with the driver wearing the shoulder belt without the lap belt fastened. Among drivers with lap and shoulder belts, the most common crash mode was the left

frontal offset. In crashes with severity around 30 mph, the centerline impact with a rigid narrow object produced liver injury.

In examining heart injuries, all available cases from the Special Crash Investigations file maintained by NHTSA were included. For heart injuries in low to moderate severity crashes, impacts with rigid narrow objects was the most common crash mode. Impacts with soft structures such as the rear and side of other cars were also heart injury producing crash modes.

For both liver and heart injuries, conditions which cause the occupant to be positioned close to the air bag was a recurring theme in low to moderate severity crashes.

Liver and heart injuries are frequently difficult to detect at the crash scene. If not promptly diagnosed and treated, the consequences are often fatal. A major objective of this study is to identify crash conditions beyond crash severity, which can assist in detecting the presence of these occult injuries.

## INTRODUCTION

The William Lehman Injury Research Center at the University of Miami has investigated 88 frontal crashes in which the driver air bag deployed and the driver was transported to the Ryder Trauma Center for emergency medical care. Data has been collected from the crash scene, the damaged vehicle, and the injured occupant.

The criteria for admission to the study is as follows: (1) the subject must have been involved in a frontal collision; (2) the subject must have been protected by a safety belt, an air bag, or both; (3) at the crash scene, the subject must have met triage criteria for suspicion of injuries of a severity which justified transporting to the Ryder Trauma Center; and (4) the subject must have agreed to have their records included in the study. The study included 100% of the subjects transported to the Ryder Trauma Center, which met the criteria. Less than 10% of the subjects refused to participate in the study. The decision to transport a patient to the

Ryder Trauma Center is based on the criteria listed in Table 1. If the subject meets one or more of these criteria, transport to the Ryder Trauma Center is mandated.

**Table 1.**  
**Adult Trauma Criteria**

Systolic BP < 90 (Shock)
Respiratory rate < 10 per min. or > 29 per min.
Glasgow Coma Scale < 12
Penetrating injury to head, neck, chest, abdomen or groin
Paralysis
2 <sup>nd</sup> or 3 <sup>rd</sup> degree burns > 15% TBSA
Amputation proximal to wrist or ankle
Ejection from motor vehicle
Paramedic Judgment - High Index of Suspicion of Injury

The data collected in the study provides a basis for in-depth analysis of injuries and the crashes in which they occurred. Engineering analysis of these crashes is conducted in conjunction with the National Crash Analysis Center at the George Washington University. The multidisciplinary research team includes expertise in crash investigation, crash reconstruction, computer graphics, biomechanics of injuries, crash data analysis, emergency trauma care, and all of the medical specialties associated with the Ryder Trauma Center at the Jackson Memorial Hospital. By careful study of injured crash victims, their vehicle and the crash scene, injury patterns emerge. These patterns form the basis for hypotheses which can be explored further by analysis of mass crash data, crash tests, and computer modeling. As a consequence, recommendations can be developed for injury control measures. One purpose of this study is to identify injury patterns among severely injured subjects.

#### **INJURY PATTERNS FROM NASS/CDS DATA**

The NASS/CDS is intended to provide a representative sample of crashes in the United States in which one of the vehicles was damaged sufficiently to be towed away from the crash scene. *Figure 1* shows the distribution of frontal crashes, injuries and fatalities based on NASS/CDS data, years 1988-1996.

Analysis of NASS data by NHTSA suggests several areas in which air bag performance may be lower than expected. NHTSA's *Third Report to Congress:*

*Effectiveness of Occupant Protection Systems and Their Use*, provides data on air bag effectiveness in injury reduction for different populations and body regions. Table 2 shows the likelihood of reducing moderate (AIS 2+) injuries for selected populations. The bold print indicates statistically significant differences from the risk of unrestrained occupants. Those figures not in bold print are not statistically significant. All of the effectiveness numbers are relative to the unrestrained population. The inherent effectiveness of the belt system is included as part of the AB+Belt numbers. Consequently, the AB+Belt effectiveness is expected to be higher than the 3pt Belt effectiveness.

Air-bags-plus-belts are shown to be very effective in reducing moderate injuries to belted males. However, the benefits to restrained females and older drivers is less evident.

Tables 3 shows data for injury effectiveness in reducing serious (AIS 3+) injuries, by body region.

**Table 2.**  
**The Likelihood Of Reducing Moderate Injuries For Selected Populations**

System Used	Male Drivers	Female Drivers	Drivers 50+	Drivers <65"	Drivers <135lbs
AB + Belt	<b>64%</b>	<b>59%</b>	<b>57%</b>	<b>48%</b>	<b>55%</b>
AB Only	12%	25%	9%	31%	-36%
3pt Belt	<b>38%</b>	<b>59%</b>	<b>54%</b>	<b>55%</b>	<b>42%</b>

**Table 3.**  
**Effectiveness of Occupant Protection Systems In Reducing the Likelihood of Serious Injury By Body Region**

System Used	Head	Chest	Upper Extrem	Lower Extrem.
AB + Belt	<b>75%</b>	<b>66%</b>	<b>-40%</b>	<b>78%</b>
AB Only	16%	18%	14%	-5%
3pt Belt	<b>38%</b>	<b>54%</b>	<b>28%</b>	<b>79%</b>

The data from Table 3 shows the excellent head injury protection provided by the air-bag-plus-belt. Serious chest injuries are also reduced, but to a lesser extent. The NASS/CDS data for the air bag only restraint is not statistically significant. However, reductions in serious head and chest injuries are indicated. With regard to lower extremities, the air bag plus belt has about the same effectiveness as the 3pt belt. Similarly, the air bag only has no

statistical effect in reducing lower extremity injuries.

Further analysis of NASS has been conducted to better understand air bag performance. This analysis examined the risk of AIS 3+ injury per 100 exposed drivers in frontal crashes. The injury risks for each body region are shown in Figure 2. The population not protected by air bags includes drivers in air bag vehicles who were in crashes below the threshold for air bag deployment. The presence of these non-deployment cases reduces the average crash severity for the belt only and the unrestrained populations relative to the air bag populations.

Other studies have indicated that the unrestrained population is involved in crashes that are more severe than the restrained population [Malliaris, 96]. This observation holds for the unrestrained population protected by air bags. Because of the differences in crash severity, the data in Table 2 can not be used to assess the effectiveness of belts or air bags. However, it is useful in examining the shifts in the injury distribution which can be expected in tow-away crashes when air bag deployment occurs.

Figure 2 shows a large reduction in head injuries for air bag protected drivers. Reductions in trunk injuries are less pronounced. The increased risk of lower limb injuries with air bag deployment is postulated to be indicative of the higher average crash severity for the air bag cases.

To further examine performance of air bags in NASSCDS, a more detailed examination of injuries was undertaken. The concept of average injury weighted harm per occupant was used for this analysis. Injury weighted harm is based on all injuries in the NASS 1988-95 file, each weighted according to its average cost. Table 4 shows the AIS injury weighting factors used in the analysis. These weighting factors are the average monetary cost incurred by injured persons at each AIS level and normalized for the cost of a fatality.

To calculate injury weighted harm, each injury in the population is multiplied by its weighting factor and by its NASS expansion factor and the quantities are summed. Risk per hundred exposed occupants is determined by dividing the injury-weighted harm by the NASS weighted number of crash exposed occupants with similar restraint systems. No correction for

crash severity has been included in this data. The values of injury weighted harm per occupant provide the relative magnitude of the risks for specific types of injuries. The risks of injury for individual body regions contain considerable uncertainties, but are useful in examining large differences in risk.

**Table 4.**  
**Injury Weighting Factors**  
**For Harm Calculations**

AIS Injury	AIS #	Weighting Factor
Minor	1	0.004
Moderate	2	0.034
Serious	3	0.114
Severe	4	0.218
Critical	5	0.839
Fatal	6	1.000

Table 5 shows the injury-weighted harm per crash exposed occupant for critical organs in the chest/abdomen. The critical chest/abdominal organs are the heart and liver. Injuries to these organs are time critical. If not treated immediately, serious consequences or death can result.

Table 5 indicates that the belted and belted plus air bag populations have the lowest harm risks for these critical thorax body regions. The air bag only data is not statistically significant. For the unrestrained population, the present day air bag does not appear to mitigate injuries to these critical regions of the body. The heart and liver injuries are among the most difficult to detect. By mitigating the more obvious head injuries, the residual air bag injuries become more difficult to detect.

**Table 5.**  
**The Injury Weighted Harm/**  
**Occupant for Heart, and Liver**

System Used	Harm Risk
AB + Belt	0.017
AB Only	0.227
3pt Belt	0.025
Unrestrained	0.096

## LEHMAN CENTER DATA

The distribution of Lehman Center cases by restraint use, fatalities, and average delta-V is shown in *Table 6*.

**Table 6 Lehman Center – Driver Cases 1991-97**

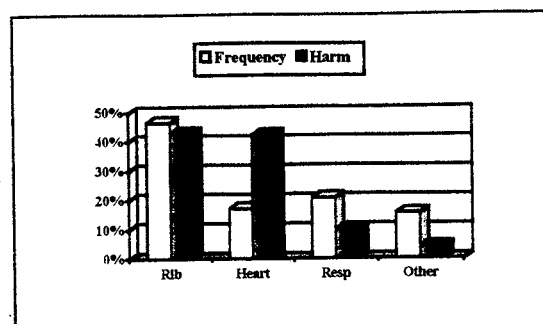
	#	Avg dV	Fatal	Avg dV	%Fatal
AB+LS	39	22.4	9	26.6	23.1
AB+Sh.	5	26.4	2	36.0	40.0
AB Only	44	25.6	12	22.8	27.3
All	88	24.8	23	28.5	26.1

*Figure 3* provides a comparison of the injury severity of subjects in the Lehman Center as compared with NASS population expanded to represent the national distribution. The Lehman Center population provides a sample of the serious and fatally injured crash victims in the Miami region. It is an extremely enriched sample of AIS 3+ injuries. As such, it provides a basis for examining injury patterns in detail and developing insights which can be further examined using other population based data systems and resources.

*Figure 4* shows the distribution of AIS 3+ injuries for the 88 air bag cases in the Lehman Center compared to NASS/CDS 1988-1996. A comparison of the frequency of fatal injuries in the NASS projected population and the Lehman population is shown in *Figure 5*. It is evident that the distributions of AIS 3+ injuries are generally similar, but The Lehman Center has more injuries in the lower crash severity ranges. The Lehman Center data also has more fatalities in the lower crash severity ranges and in the 40 to 45 mph speed ranges.

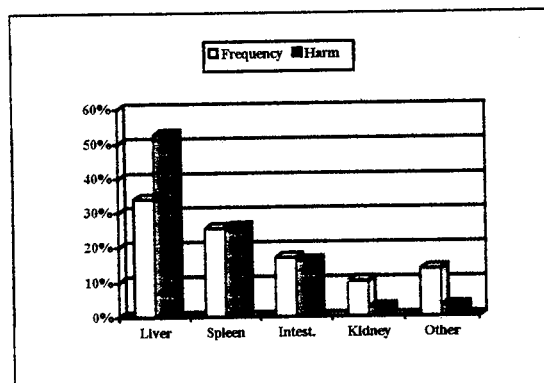
The distribution of harm by body region is shown in *Figure 6*. The trunk is the largest source of harm and will be examined in more detail. Within the trunk harm fraction, 32% of the harm is to the abdomen, and 68% to the chest.

*Figure 7* shows the distribution of harm



**Figure 7. Harm Distribution within Chest Region**

within the chest region. Heart and ribs are the largest chest sources of chest harm. *Figure 8* shows the distribution of harm within the abdominal region. Liver and spleen are the largest harm fractions.



**Figure 8. Harm Distribution within Abdominal Region**

## PATTERNS OF LIVER INJURIES

The Lehman Center data contains 17 drivers with air bag deployment in frontal crashes **Figure 7. Distribution of Harm and Liver Injury**

and liver injuries. Seven of these cases were fatalities. Nine drivers were restrained by lap and shoulder belts plus air bag, five were restrained by shoulder belt plus air bag, and three had only the air bag. Characteristics of the crashes with liver injuries are summarized in Tables 7, 8 and 9. The delta-V (dV) listed in these tables is crash severity in mph. The principal direction of force (PDOF) is the clock direction.

**Table 7.**  
**Liver Injury Cases - Lap + Shoulder Belt Restrained Drivers**

Case #.	dV	Age	Sex	Fatal	PDOF	Type	Remarks
96-013	19	54	F	No	11	Left Offset	12" L.I.P. Int. (Truck)
94-010	20	19	M	Yes	11	Left Offset	27" Header Intr. (PU)
97-021	21	32	F	No	11	Left Offset	High G Crash (Truck)
92-023	22	50	M	No	12	Left Offset	CCW Spin Post crash
95-016	29	39	M	No	12	Ctr Narrow	High G Crash (Close in)
97-014	30	20	M	No	12	Ctr Narrow	High G Crash
95-001	33	37	M	No	11	Left Offset	12" L.I.P. Intrusion
96-001	38	66	F	Yes	12	Left Offset	22" L.I.P. Intrusion
96-002	38	72	F	Yes	12	Left Offset	Severe Crash

The cases of lap & shoulder belt protected drivers with liver injuries fall into three crash severity categories. There are four cases with crash severity below 23 mph, two cases with crash severity around 30 mph, and three cases with delta-V above 32 mph.

The two 38-mph cases both involved severe intrusion of the driver side instrument panel and deformation of the steering column. Fatalities from multiple injuries resulted in both cases. Older occupants were involved in both of these cases. A third case, at 33 mph exhibited the same crash pattern and compartment intrusion as the two 38-mph crashes, but the younger occupant survived at this lower crash severity.

Both of the subjects in 29 and 30 crashes survived. Both were in frontal impacts with narrow objects - a condition which produces a severe acceleration late in the crash pulse. The air bag deployment may be delayed in such a crash. This type of crash also produces high loading by the safety belt.

Case 96-013 was an override by a heavy truck. The delta-V was 19 mph, but 12

inches of A-pillar intrusion resulted. In addition to a liver laceration, the driver suffered head and lower extremity injuries.

Case 94-010, was an override of a small car by a pickup truck. The windshield header was displaced 27 inches into the occupant compartment. The belted driver died from multiple head and chest injuries caused by the intruding pick-up truck. This case illustrates how delta-V may not adequately predict the severity of the crash environment experienced by the occupant in certain types of real world crashes. This case also produced a heart injury that is included in the section to follow.

Case 97-021 was a 21-mph left offset collision of a minivan with a heavy truck. Approximately 5 inches of dashboard intrusion resulted. An AIS 4 liver injury resulted.

One case, 92-023, involved an impact with the rear of a stationary car. The left rear of the stationary car was on a jack for a tire change. A delayed air bag deployment may have resulted from a soft crash pulse followed by a CCW spin.

**Table 8.**  
**Liver Injury Cases - Unrestrained Drivers**

Case #.	dV	Age	Sex	Fatal	PDOF	Type	Remarks
92-006	20	34	M	No	12	Right Offset	Mild Crash Pulse
93-026	23	67	M	Yes	1	Full Frontal	Close-in
96-017	45	40	F	Yes	12	Left Offset	Severe Crash

Table 8 shows the crashes of unrestrained drivers with air bag deployment. Of the three unrestrained cases, one was extremely severe, and

the other two drivers were believed to be close to the air bag at the time of deployment.

The crash in Case 96-017 was severe and loss of occupant compartment integrity resulted

The vehicle in case 92-006 impacted a residence wall and the left front of the car entered through a sliding glass door. The air bag deployment was probably delayed by the mild crash pulse. Consequently, it is likely that the unrestrained driver was close to the deploying air

bag. The liver injury was not discovered at the scene and no medical treatment was provided until the subject passed out at a police station.

The driver in case 93-026 was observed to be close to the steering wheel before the impact. This driver also sustained a fatal heart injury.

**Table 9.**

**Liver Injury Cases - Shoulder Belt Only Drivers**

Case #.	dV	Age	Sex	Fatal	PDOF	Type	Liver Injury
97-049	12	32	M	No	1	*RF	R. Lobe
94-005	16	39	F	No	12	RF	R. Lobe
93-020	32	53	F	No	1	RF	R. Lobe
97-023	34	70	M	Yes	12	Full Frontal	R. Lobe
96-045	38	23	F	Yes	1	RF	R. Lobe

\*RF= Right Front

Table 9 lists five drivers with shoulder belt only, and air bag deployment. These cases form a distinct pattern of liver injury. In all cases, the injury occurred to the right rear lobe of the liver. This injury pattern was similar to that reported earlier (Augenstein, 1995). The injury is attributed to loading by the shoulder belt. In lower severity crashes the damage was to the right front of the car. As the crash severity increases to 25 mph other damage patterns are observed.

## HEART INJURY CASES

The Lehman Center data contains eight cases with heart injury. Seven of the cases were fatalities. Four of the occupants were restrained by lap and shoulder belts and four were unrestrained.

Characteristics of the cases in which the drivers were restrained by lap and shoulder belts are shown in Table 8.

**Table 10.**

**Heart Injury Cases - Restrained Drivers**

Case #	dV	Age	Sex	Fatal	PDOF	Type	Remarks
97-013	17	78	M	Yes	2	R. Corner	Right Sideslap (SUV)
94-010	20	19	M	Yes	11	L Offset	27" Header Intrusion (PU)
92-017	37	63	M	No	11	Offset	Occult Injury
96-001	38	66	F	Yes	12	Offset	22" Dash Int.

Two of the fatalities in the restrained cases involved massive intrusion of the occupant compartment or complex multiple impacts. The air bag did not contribute to increasing or reducing the chest injuries in these cases. Case 97-13 was an impact between the right front of a small car and the front of a sport utility vehicle. Counter-clockwise rotation followed by a side slap resulted. The side loading by the belt may have induced the liver injury.

The survivor, Case 92-017 was in a very severe crash. He had no head injuries. His only apparent chest injuries were fractures of the right

anterior ribs 2, 3, & 4. There was no initial vital signs to indicate that a heart injury had occurred. His heart injury was not recognized until deterioration in his condition occurred. This case illustrates one of the characteristics of air bag protected occupants. In the absence of major head injuries and rib fractures, the presence of internal injuries may be difficult to detect at the scene.

Characteristics of the cases in which the drivers were unrestrained are shown in Table 11.

Table 11.

## Heart Injury Cases - Unrestrained Drivers

Case #.	dV	Age	Sex	Fatal	PDOF	Type	Remarks
93-026	23	67	M	Yes	1	Full Frontal	Close-in
97-036	26	63	M	Yes	12	Complex	Missed Air Bag
94-007	37	20	M	Yes	1	Multiple Crash	Missed Air Bag
97-043	46	29	M	Yes	11	Full Frontal	High G Pulse (Van)

Two of these cases, 97-036, and 94-007 involved crash forces which caused the unrestrained occupant to miss the air bag and impact the interior surfaces on the vehicle. Case 97-043 was a severe crash which caused loss of integrity of the occupant compartment.

Case 93-026 was a 23-mph frontal crash in which the occupant was close to the steering wheel. The air bag probably contributed to the heart injury.

A study of heart injuries in the NHTSA Special Crash Investigations file was undertaken to supplement the Lehman data.

## AIR BAG CASES WITH HEART INJURY - NHTSA SPECIAL INVESTIGATIONS

The NHTSA Special Crash Investigations file contains records of 1258 drivers who were in vehicles with air bag deployment. The criteria for inclusion in this file is varied. Consequently, it is not possible to extrapolate results determine frequency of occurrence. However, the file is useful for examining injury patterns, which can be compared with nationally representative files.

Table 12.

## Summary of Heart Injury Cases from Special Studies

Case No	Yr	Make	Model	DV	AIS	objstruck	AGE	Contact	FATAL	Belt?
CA8933	89	Mercedes-Benz	300/500	-11	4	TREE	44	IP	Y	Y
CA9109	91	Ford	Taurus	7.7	5	83 BUICK RIVIERA	79	AB ???	Y	Y
NC9307	91	Chevrolet	Corsica	8	5	TREE	78	AB	Y	N
CA9303	91	Mercury	Capri	9	5	89 CHRYSLER	22	AB	N	N
DS9422	94	Chevrolet	Corsica	11	6	90 ECLIPSE SIDE	73	AB	Y	Y
IN9506	90	Lincoln	Continental	12	5	VAN	38	AB	Y	N
CA9112	90	Dodge	Shadow	14.4	3	UTILITY POLE	36	SEAT	Y	Y
CA9309	90	Ford	Taurus	16	5	CAR	71	AB	Y	N
DS8912	85	Ford	Tempo	17.6	4	CAR REAR	53	AB	Y	N
CA9110	91	Pontiac	Firebird	18.9	4	TREE	46	AB??	Y	Y
CA9502	94	Ford	F-150	19	4	CAR REAR	56	AB	Y	N
IN9407	92	Oldsmobile	Delta 88	22	5	TREE	68	AB/SW	Y	Y
DC9012	90	Ford	Taurus	25.3	3	VEHICLE TWO	21	SW	N	Y
IN9201	91	Chevrolet	Impala	32.4	5	CAR	48	SW	Y	N
DC9108	90	Dodge	Charger	33.5	5	VEHICLE 2 ESCORT	49	SW	Y	N
CA8951	89	Dodge		60.2	4	SUPPORT PILLAR	24	UNK	N	N
SW8922	87	Mercedes-Benz	200/300	HI	5	UTILITY POLE	42	L SIDE	Y	N

The file contains 56 cases with fatal injuries. Fifteen of these (27%) had severe heart injuries. Among the fatals with severe heart injury, 67% were at crash speeds of less than 20 mph. Six were at crash severities of less than 15 mph. In addition to the fatal injuries, there were

3 drivers with AIS 3+ heart injuries who survived. One of these was at a crash speed below 10 mph.

A summary of the drivers with heart injury documented in the NHTSA Special Study is shown in Table 11.

The data from Table 11 indicates 12 cases of heart injury at crash speeds below 22 mph. Five of these were impacts with poles. Two were impacts with the rear of another car. These types of crashes produce relatively low acceleration crash pulses, which may delay the deployment of air bags. It is possible that the occupant may have been close to the deploying air bag in these cases.

In the data from Special Studies of Air Bag Crashes, heart injuries represent about 1% of the injuries but 26% of the fatalities. The majority of these fatalities occurred at crash speeds below 22 mph. Crashes involving poles and car front to car rear are over represented in these low speed crashes. Older persons are also over represented. Combinations of these factors may be useful in suspecting the presence of rare, but serious heart injuries.

## DISCUSSION OF LIVER INJURY CASES

Of the nine cases of lap and shoulder belt restrained occupants, 6 were at crash severities less than 31 mph. Five of these were impacts with trucks or trees - events which produce high g crash pulses and/or steering column and instrument panel intrusion. Two patterns appear to emerge from these data - left offset crashes with trucks and pickups (below 25 mph), and frontal crashes with rigid narrow objects (at around 30 mph).

Of the two cases of unrestrained occupants at crash severities less than 24 mph, close proximity to the air bag at deployment appears to be a common pattern. In one case, a late deployment was probable. In the other case, the driver was positioned close to the wheel prior to the crash.

Of the five cases of shoulder belt restrained occupants, the crash and injury patterns were similar - right front vehicle damage, and right side liver damage. This pattern of crash and injury has been observed earlier, and has been attributed to shoulder belt loading.

Of 17 cases involving liver injury, the air bag may have contributed to the injury in two cases involving unrestrained occupants in crashes below 23 mph. The shoulder belt only may have contributed to two liver injuries at crash severities below 17 mph and three above 30 mph.

Most of the liver injuries (59%) occurred at crash severities of 30 mph or less. However, in several cases the delta-V was not a suitable measure of the violence of the crash.

## DISCUSSION OF HEART INJURY CASES

There are eight heart injury cases in the Lehman Center data. Seven of them were fatal. It is expected that heart injury occur primarily in very severe crashes. Six of the eight crashes were very severe - either with crash severity greater than 37 mph, or with extensive intrusion or complex non-frontal motion. In two of the severe cases, the unrestrained occupant missed the air bag and impacted hard interior structures.

The air bag probably caused the injury in one of the eight cases. In this case, the older driver was close to the bag at deployment, and was fatally injured.

In the special studies data, 80% of the heart injuries occurred at crash severities less than 22 mph. Of 12 cases, 5 were impacts with poles or trees, and 2 were with the rear of another car. Late deployment of the air bag is most likely in low severity crashes with narrow objects, relatively soft objects, or objects moving in the same direction.

## CONCLUSIONS

Vehicles equipped with air bags provide large reductions in head injuries. They also provide injury reduction for chest and abdominal injuries, but to a lesser extent.

For unrestrained drivers, the residual severe chest/abdominal injuries are more likely to be to the heart and liver than if the driver is belted. The presence of a deployed air bag appears to reduce critical head injuries for the unrestrained driver. However, critical injuries to the heart and liver may not be reduced significantly. The presence of these injuries are frequently difficult to detect at the scene.

In the census of cases involving drivers protected by air bags in frontal impacts at the Lehman Center, 44% of the injury weighted harm was from chest/abdominal injuries. The chest comprised 68% and the abdomen 32% of this harm fraction. In examining the harm to the chest, the ribs and heart each made up about 43% of the harm. In examining the abdomen, the liver contributed 53% and the spleen 26%.

Heart injuries occurred in 9% of the cases, and liver injuries occurred in 19% of the cases. These two injury modes, along with rib fractures, were the most harmful chest/abdominal injuries.

The most distinct injury pattern observed was injury to the right lobe of the liver induced in drivers wearing their shoulder belt only - without



the lap belt fastened. In all of the shoulder belt only cases with air bags, the predominate damage was to the right front of the car. Liver injuries in these types of crashes have been shown to be induced by shoulder belt loading [Augenstein 1995]. The air bag did not prevent these belt induced injuries.

For belted drivers protected by air bags, frontal centerline impacts with rigid narrow objects at crash speeds close to 30 mph produced liver injuries. These types of crashes produce higher than normal acceleration forces at the 30 mph severity level. As a result, higher belt loading and possible delayed air bag deployment may result.

The left-offset frontal crash with heavier vehicles was the most frequent crash type in crashes less severe than 21 mph. Extensive intrusion of the steering wheel and left instrument panel occurred in these cases. The normal delta-V may not be an adequate indicator of crash severity in these crash modes. Additional indicators of the crash severity are needed to predict these higher risk cases.

For unbelted drivers, pre-crash conditions that produced close proximity with the deploying air bag were the common thread in the low severity crashes with liver injuries. Identification of conditions which position the driver close to the air bag.

Seventy-five percent of heart injuries in the Lehman Center data were in severe crashes. However, the air bag was implicated for one unrestrained driver who was close to the air bag in a moderate severity crash. In order to gain a larger sample of heart injuries, cases from the NHTSA Special Crash Investigations file were included. The low severity events that produced heart injuries were impacts with fixed narrow objects, and with the rear of other vehicles. Both of these types of crashes can result in delayed air bag deployments. Older drivers were over represented among the cases with heart injuries. Driver age and position relative to the air bag appear to be critical factors, independent of delta-V.

The combination of data from the William Lehman Injury Research Center with data from NASS/CDS and SCI files provides valuable insights into injury patterns among air bag protected occupants and crash characteristics that produce the injuries.

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# IMPROVING SAFETY PERFORMANCE IN FRONTAL COLLISIONS BY CHANGING THE SHAPE OF STRUCTURAL COMPONENTS

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## ABSTRACT

The design optimisation of vehicle structures for improved crashworthiness is very much a trial and error process. A method of structural optimisation is described which is a more formal and systematic approach to design improvement. The method is implemented into an existing optimisation program and is used to improve the response of structural components within a vehicle by changing their shape. A sensitivity analysis based on the elastic buckling response of a structural component drives shape changes in the optimisation process.

The program is applied to improving the crashworthiness of a box section member. The optimised component shows a substantial increase of the initial collapse load and energy absorbing capacity. Results from dynamic simulations confirm this.

## INTRODUCTION

Techniques for *analysing* the behaviour of vehicle structures in a collision are well established within the car industry, however, techniques for *improving* this behaviour are still very much in an infancy. Outcomes of recent work by Satoh *et al* (1996) and Witteman *et al* (1996) typify the current methods employed for design improvement. The authors presented a set of guidelines governing the wall thickness and section width of structural components for optimal energy absorption. While reducing the trial and error involved in design, such guidelines only provide a qualitative measure of the design changes required.

A more advanced procedure for improving the crashworthiness of vehicle structures was proposed by Hagiwara *et al* (1990). A sensitivity analysis was used to study the change in buckling response of a structural component with variations in wall thickness. While no quantitative measure of improved performance was determined, the authors found that general design studies were possible with the use of a sensitivity analysis based on the buckling load of a structure. Kitagawa *et al* (1992) used a similar concept to improve the dynamic buckling

load of a straight beam, however, the cross-sectional area was varied instead of the wall thickness.

This paper extends the use of a sensitivity analysis in relation to improving the crash safety of a vehicle. Unlike Hagiwara *et al* and Kitagawa *et al*, the sensitivity analysis is used to calculate the effect of shape changes on the buckling response of a structural component. This information is coupled with a structural optimisation program to enable the integrated redesign of components.

The program is used to change the shape of a box section member. For this case, the effects of an increased buckling load on crush characteristics such as the initial collapse load and energy absorbing capacity are investigated as a function of the impact speed. Results are correlated with a theoretical formulation governing the role of the impact speed.

## STRUCTURAL OPTIMISATION - A SYSTEMATIC METHOD FOR DESIGN IMPROVEMENT

### Background

Structural optimisation techniques are used herein to provide a systematic method for improving the crashworthiness of a vehicle structure. Numerous references are available on the topic (for example: Vanderplaats, 1984) and as such, only the key concepts and terms are defined below:

1. *Objective function*: the performance measure of a structure which is desired to be maximised or minimised.
2. *Design variables*: variables which govern the design of a structure such as material thickness and geometry.
3. *Constraint function*: a restriction on the response or design variables of a structure.
4. *Sensitivity*: a quantitative measure on how the response of a structure is affected by changes in design variables.

## Computational Basis

The computer program RESHAPE is an example of a structural optimisation program. This program is centred on the finite element method and utilises sensitivity data to search for the optimum shape of a structure (Tomas *et al*, 1991). The objective function for this process can be chosen from performance measures such as stress, frequency and mass. Shape changes are described by selected node coordinates on a finite element model. Thus, arbitrary shape variations can be achieved in the optimisation process. Mesh integrity and boundary smoothness is retained through the use of parametric cubic geometry which overlays the finite element model. Additionally, the program enables constraints to be applied as limits on the response of a structure, as direct limits on design variables and as function constraints. The function constraints are used to maintain design requirements such as a symmetric geometry or a prismatic cross-section.

The aforementioned program will be extended to enable the design improvement of vehicle structures. This task will require the definition of a suitable objective function which characterises the crashworthiness of a vehicle structure.

## BUCKLING LOAD AS AN OBJECTIVE FUNCTION

### The Role of Buckling in Crash Safety

In a vehicle, there are Key Structural Components (KSC's) which absorb a significant amount of crash energy and influence the behaviour of a vehicle structure

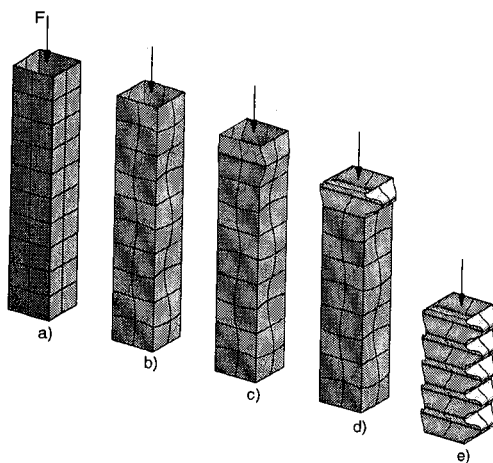


Figure 1. Sequence of axial column crush a) loading, b) buckling, c) edge yielding, d) folding and e) continuation.

during a collision. Improving the performance of these components will therefore improve the crash safety of a vehicle as a whole.

In the initial stages of a collision, predominantly axial loads are transferred to the KSC's. The following transpires as the collision advances (see Figure 1 and Figure 2):

- The compressive stresses in the KSC's begin to increase rapidly as the applied axial load increases.
- A critical load is reached where the walls buckle on the weakest KSC.
- The edges of this KSC carry the increasing axial load as a result of the buckled walls. Edge yielding eventuates. In general, this occurs directly after buckling.
- The load carrying capacity of the KSC drops as the walls fold.
- Continuing (secondary) buckling, edge yielding and folding occurs as the energy from the collision is absorbed.

The onset of buckling triggers the initial collapse of a KSC. However, the actual load  $F_{max}$  at which this occurs depends not only on the elastic buckling load, but on the impact velocity and yield load as well. This dependence can be quantified by the following equations (see Appendix for derivation):

$$\text{When } F_b < F_y: F_{max} = \begin{cases} f(F_b, V), & \text{for } V \leq V_c \\ F_y, & \text{for } V > V_c \end{cases} \quad (1.)$$

$$\text{When } F_b \geq F_y: F_{max} = F_y, \text{ for all } V \quad (2.)$$

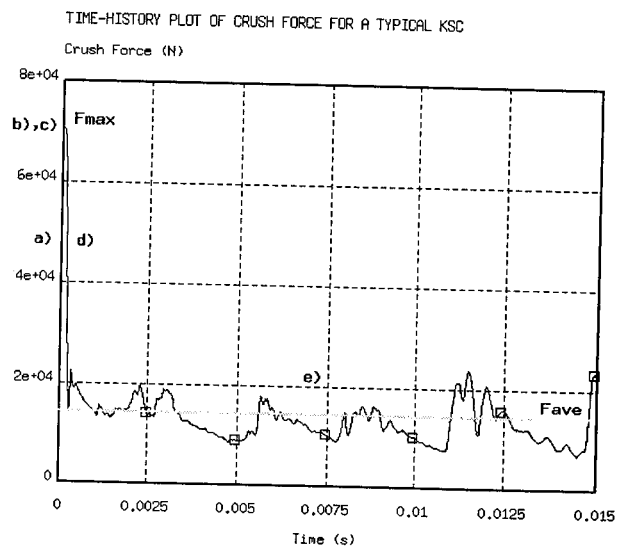


Figure 2. Typical time-history plot for the crush of a KSC.

where  $V$  is the impact velocity,  $F_b$  is the buckling load,  $F_y$  is the yield load and  $V_c$  is the critical impact velocity.

With reference to equation (1.), in a high speed impact ( $V > V_c$ ) the initial collapse load is characterised by the yield load because stresses generated from the impact are sufficient to cause plastic deformation. Buckling, therefore, occurs after the onset of yielding and does not influence the initial collapse load. In the case of a low velocity impact ( $V \leq V_c$ ), buckling transpires before stresses induced from the collision have time to reach the elastic limit. Hence, the elastic buckling load influences the initial collapse load in this instance.

Based on the preceding discussion, it is postulated that design changes based on improving the elastic buckling load of a KSC will also improve its initial collapse load in a low speed impact. This is an important aspect of crashworthiness because an elevated initial collapse load reduces the possibility of any permanent structural damage in low speed collisions.

### Secondary Influences of Design Changes Based on the Elastic Buckling Load

Apart from the initial collapse load, another important aspect of crashworthiness is the energy absorbing capacity of a KSC. This reflects on the potential of vehicle structure to absorb crash energy. Therefore, improving the energy absorbing capacity of a KSC will enhance the safety performance of a vehicle as a whole.

The energy absorbing capacity of a KSC is primarily characterised by the average force  $F_{ave}$  at which secondary buckling, edge yielding and folding occurs (see Figure 1 and Figure 2). It is predicted that design changes which improve the elastic buckling load of a KSC will also improve the average force required to crush the KSC. This is because the walls of an optimised KSC have a high resistance to bending, even after initial collapse. Hence:

1. a higher compressive load will be required to cause secondary buckling of the walls,
2. bending deformations will be reduced and therefore edge yielding will take place at a higher load and
3. folding of the walls will require more work due to their increased bending stiffness.

### Calculating the Elastic Buckling Load and Related Sensitivity Data

To implement an elastic buckling objective in the optimisation program requires calculation of the buckling load and related sensitivity data. The load at which

elastic buckling occurs is calculated from the following characteristic eigenvalue equation by the finite element method (Cook *et al*, 1989):

$$(K + \lambda K_\sigma)u = 0 \quad (3.)$$

where  $K$  is the stiffness matrix,  $K_\sigma$  is the initial stress matrix,  $\lambda$  is the eigenvalue and  $u$  is the eigenvector. The eigenvalue  $\lambda$  is proportional to the buckling load.

By differentiating equation (3.) with respect to the design variables  $x$ , an expression relating the variation of buckling load with respect to changes in the shape of a structure is obtained:

$$\frac{d\lambda}{dx} = \frac{u^T \left( \frac{dK}{dx} + \lambda \frac{dK_\sigma}{dx} \right) u}{u^T K_\sigma u} \quad (4.)$$

This equation is used for calculation of the sensitivity data.

### The Order of Elastic Buckling

An eigenvalue analysis based on equation (3.) yields many buckling loads and related mode shapes. Only the first buckling load is considered in static applications as this is always the critical value. However, in dynamic situations such as the collapse of a KSC, higher order buckling modes have been found to influence the collapse behaviour (Kitagawa *et al*, 1992).

While the capability exists to optimise higher order modes, the approach adopted in this paper is to use only the first buckling load as the objective function in the optimisation program. This is for two reasons. Firstly, an improvement in the buckling response for the first mode will inevitably improve the response in higher order modes as well. Secondly, the theoretical lower bound for the initial collapse load is the first buckling load (in cases where  $F_b < F_y$ ). Therefore, increasing this lower bound will ensure that there is no possibility of failure at a lower load.

### Limitations of an Elastic Buckling Analysis

The foregoing discussion was primarily related to the axial collapse of a straight KSC with a uniform cross-section. While the design optimisation of such members will lead to the improved safety performance of a general vehicle structure, in some cases it may be desirable to enhance the collapse behaviour of KSC's with a varying cross-section or curved profile. Optimisation based on the elastic buckling load must be approached with caution

in these cases. This is because the solution of equation (3.) requires the existence of a bifurcation point. In addition, equation (3.) is derived on the basis that any bending deformations prior to buckling are negligible. Hence, an elastic buckling analysis may not properly characterise the failure of a KSC's with an arbitrary geometry.

### IMPROVING THE CRUSH RESPONSE OF A BOX SECTION MEMBER

The following example is presented to illustrate the capabilities of the shape optimisation program with the elastic buckling load as an objective. It also serves to substantiate the previous inferences made on the relation between the elastic buckling load and dynamic response of a KSC.

#### Optimising the Design

Details of the box section member are shown in Figure 3. The first step in improving the crush response of the member was to create a finite element model for the optimisation program. This was meshed with approximately 3000 quadrilateral elements. The base of the member was rigidly fixed and a compressive axial load was applied to the top of the tube in order to simulate the force from the impact. Design variables for the optimisation process were based on the cross-sectional shape of the member. Constraints were imposed to keep the cross-section prismatic and of a constant area.

Figure 4 shows the cross-section of the optimised member. The elastic buckling load for this design is 310kN as compared to 27kN for the original design. The yield load in both cases is 67kN (assuming a uniform stress distribution and ignoring strain hardening effects).

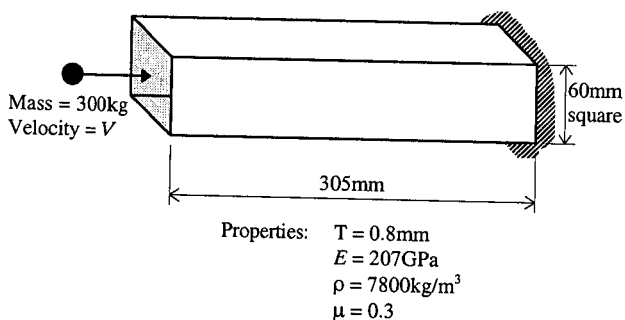


Figure 3. Details of axial crush example.

### Analysis of Collapse Behaviour

The original and optimised models of the box section member were transferred to an explicit finite element program to enable a comparison of the crush characteristics. An elastic-plastic material model was used which had a yield stress of 350MPa, hardening modulus of 450MPa and hardening exponent of 0.5. Results from the analysis are presented in the ensuing sections.

#### Improvements in the Initial Collapse Load

Figure 5 shows a plot of the initial collapse load versus impact velocity for both the original and optimised designs. A number of observations can be made from this:

1. The initial collapse load of the original design varies linearly with the impact velocity below approximately 8km/h. The initial collapse load approaches the elastic buckling load of 27kN as the impact velocity approaches zero.
2. Above an impact velocity of 8km/h, the initial collapse load of the original design is equal to its yield load of 67kN.
3. The initial collapse load of the optimised design is equal to its yield load of 67kN, irrespective of the impact velocity.
4. The optimised design has a higher initial collapse load than the original design for impact velocities below 8km/h. Hence, design changes based on the elastic buckling load are effective in improving the initial collapse load of the box section member.

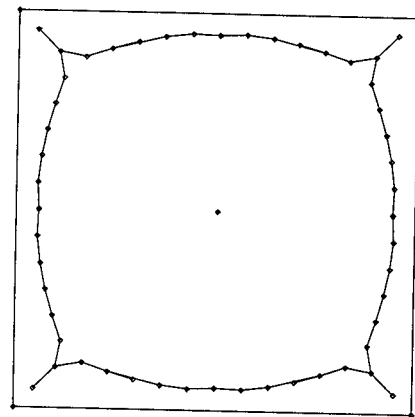


Figure 4. Optimised cross-section in comparison to original square cross-section.

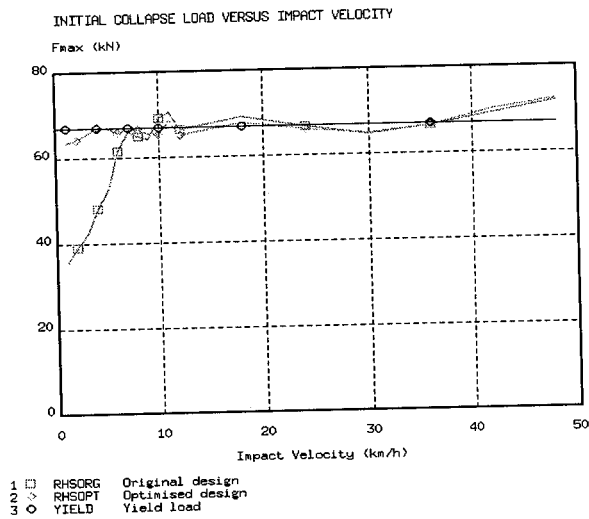


Figure 5. Initial collapse load as a function of impact velocity for the original and optimised designs.

Based on the first two observations, a relation describing the initial collapse load of the original design as a function of impact velocity can be derived (based on equation (1.)):

$$F_{max} = \begin{cases} (27 + 5V)kN, & \text{for } V \leq 8 \text{ km/h} \\ 67kN, & \text{for } V > 8 \text{ km/h} \end{cases} \quad (5.)$$

Similarly, with reference to the third observation, the initial collapse load of the optimised design can be written as:

$$F_{max} = 67kN, \text{ for all } V \quad (6.)$$

using equation (2.).

### Improvements in the Energy Absorbing Capacity

A time-history plot of the crush force for an impact velocity of 48km/h is shown in Figure 6. The average crush force for the optimised design is 91% higher than for the original design. Hence, secondary effects of design changes based on the elastic buckling load are immediately obvious. The deformed shapes of the original and optimised designs are depicted in Figure 7 and Figure 8 respectively. The higher frequency of folding and reduced bending deformations substantiates the increased bending stiffness of the walls on the optimised KSC.

Table 1 lists the average crush force (and thereby a measure of the energy absorbing capacity) for additional impact velocities. In all cases, the optimised design is significantly better.

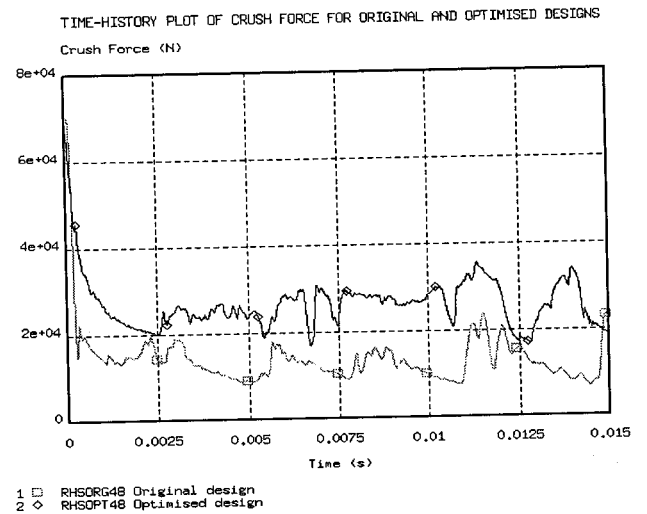


Figure 6. Time-history plot of crush force for original and optimised designs at an impact velocity of 48km/h.

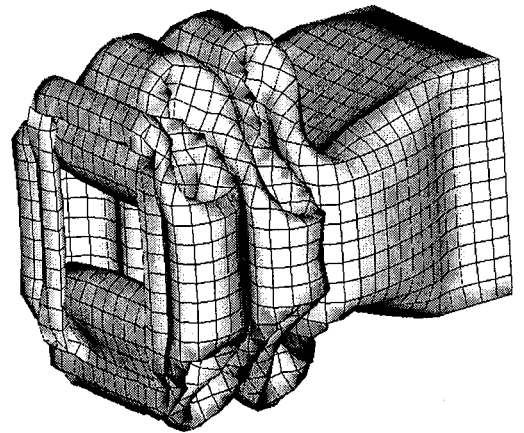


Figure 7. Crushed shape of original design due to impact at 48km/h.

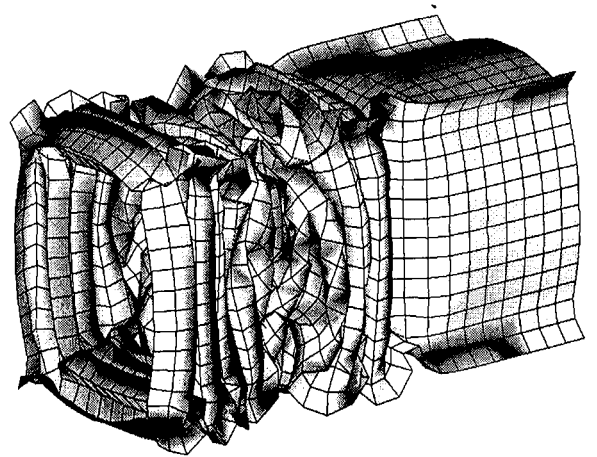


Figure 8. Crushed shape of optimised design due to impact at 48km/h.

Table 1.

Average Crush Force for Original and Optimised Members  
at Different Impact Speeds

Impact Speed $V$ (km/h)	Original $F_{ave}$ (kN)	Optimised $F_{ave}$ (kN)
12.0	15.5	24.1
18.0	14.4	22.8
24.0	14.0	22.8
32.0	13.0	23.6
36.0	13.3	25.4
42.0	13.8	26.4
48.0	13.9	26.6

## CONCLUSION

A method of structural optimisation was developed for improving the elastic buckling load of a structural component by changing its shape. It was predicted that design changes based on the elastic buckling load would increase the initial collapse load and energy absorbing capacity of structural components in a collision. These postulates were confirmed through the optimisation of a box section member. The elastic buckling load of this component was increased from 27kN to 310kN by changing the shape of its cross-section while keeping the area constant. This resulted in a 91% increase in the energy absorbing capacity of the member for an impact at 48km/h. A significant increase was also seen in the initial collapse load for low impact velocities. Given these results, the method of structural optimisation was shown to be an effective design tool for improving the crashworthiness of structural components.

## FUTURE WORK

Numerous other applications exist for the shape optimisation program in relation to improving the crashworthiness of a KSC. For example, the capability exists to optimise KSC's with a varying cross-sectional area or curved profile. Other constraints can also be implemented to achieve a design which is more manufacturable. Furthermore, the optimisation problem can be restated as "minimise mass while keeping the buckling load constant" in an effort to produce lightweight components with equivalent crush characteristics. Hence, future work will be directed towards characterising a general class of problem where design changes based on the elastic buckling load will yield improvements in crashworthiness.

## ACKNOWLEDGMENTS

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## APPENDIX

### An Equation for the Initial Collapse Load

An equation for the initial collapse load of a KSC can be developed by considering the stress induced in a KSC as a function of impact velocity. This problem is categorised as a wave propagation problem because the initial collapse occurs at a time shortly after impact when the stress wave effects are dominant.

Figure 9 shows the initiation of a one dimensional stress wave in a KSC. After time  $\Delta t$ , the stress wave has travelled:

$$\Delta x = c\Delta t \quad (\text{A-1.})$$

where  $c$  is the acoustic wave speed. Also after time  $\Delta t$ , the end of the KSC will have moved a distance:

$$\Delta l = V\Delta t \quad (\text{A-2.})$$

where  $V$  is the impact velocity (and is assumed constant).

Assuming a one-dimensional stress distribution and ignoring strain hardening and strain rate sensitivity effects, Hooke's law can be written for this problem as:

$$\begin{aligned} \sigma &= E\epsilon \\ &= E \frac{\Delta l}{\Delta x} \end{aligned} \quad (\text{A-3.})$$

where  $\sigma$  is stress,  $E$  is Young's modulus and  $\epsilon$  is strain. Substituting equations (A-1.) and (A-2.) into equation (A-3.) and taking the limit as  $\Delta t$  and  $\Delta x$  approach zero yields:

$$\sigma = \frac{EV}{c} \quad (\text{A-4.})$$

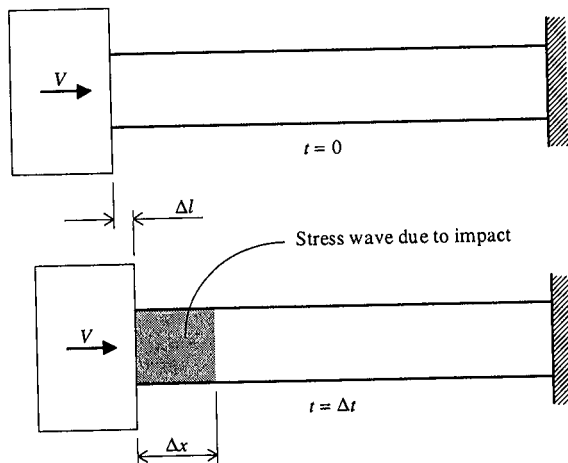


Figure 9. Stress wave propagation in a KSC due to axial impact .

Hence, the stress induced in a KSC is proportional to the impact velocity. This equation can be used to characterise the initial collapse load of a KSC depending on its buckling load.

**Case 1 -  $F_b < F_y$ :** When the buckling load of a KSC is lower than its yield load, the initial collapse load will depend on the impact speed. A high impact velocity will generate a stress wave which causes instant plastic deformation, irrespective of the buckling load. However, a low speed impact will permit buckling prior to yielding. Using equation (A-4.), the critical impact velocity below which buckling will occur is defined as:

$$V_c = \frac{c\sigma_y}{E} \quad (\text{A-5.})$$

This equation forms an upper bound to the critical impact speed. Three dimensional effects, reflection of the stress wave from boundaries and the finite time period required for a structure to buckle all affect the accuracy of equation (A-5.). A correction parameter  $\alpha$  can be introduced to account for these factors:

$$V_c = \frac{\alpha c\sigma_y}{E} \quad (\text{A-6.})$$

Hence, the initial collapse load can be written as:

$$F_{max} = \begin{cases} f(F_b, V), & \text{for } V \leq V_c \\ F_y, & \text{for } V > V_c \end{cases} \quad (\text{A-7.})$$

Note in equation (A-7.) the general function  $f(F_b, V)$  describing the initial collapse load. This is because the initial collapse load is not only a function of the buckling load below the critical impact velocity, but of the impact speed as well. The derivation of this relation is not in the scope of this paper and is a subject of future research.

**Case 2 -  $F_b \geq F_y$ :** In the case where the buckling load  $F_b$  of a KSC is greater than its yield load  $F_y$ , the stress wave generated from the impact will always reach the elastic limit before buckling occurs. This is true even for low impact speeds (assuming a constant impact velocity), because the stress wave will reflect from boundaries and compound. The yield stress will be eventually reached. Hence, the initial collapse load is defined as:

$$F_{max} = F_y, \text{ for all } V \quad (\text{A-8.})$$



# THE OFFSET CRASH TEST -A COMPARATIVE ANALYSIS OF TEST METHODS

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Paper Number 98-S1-O-08

## ABSTRACT

This research will discuss the issue of how the currently used frontal crash tests correlate to actual accidents. The following data will be presented in relation to this:

1. Results of offset crash tests now being conducted, and results of vehicle-to-vehicle crash tests, especially results of crash tests in which the vehicles have different weights.
2. Why do such differences occur?
3. Differences between the results of tests with moving deformable barriers (MDB) which are being studied by the National Highway Traffic Safety Administration (NHTSA) and results of vehicle-to-vehicle crash tests.
4. Results of modifications to test methods

The following aspects of the above mentioned issues will be discussed:

1. Important items and information to be considered in studying crash test methods to be used in the future.
2. Information which needs to be taken into consideration in developing cars in the future.

## INTRODUCTION

In response to the need to improve crashworthiness, various countries have proposed and implemented a variety of test methods in order to provide regulations and safety information. Recently, offset crash tests have come into widespread use in addition to full frontal crash tests or oblique impact tests. In actual accidents, chassis deformation and intrusion into the cabin has been observed in many cases. In addition, passenger deaths have been reported in conjunction with chassis and cabin deformation. Therefore, with the primary objective of securing cabin space and thereby reducing passenger deaths, a great deal of research has been conducted on offset crash tests, as well as on the body frame structure in order to improve passenger survivability. Full frontal crashes are considered useful for evaluating the performance of safety devices which restrain passengers during a crash. Offset crashes are considered appropriate for evaluating cabin deformation caused by the impact loads on the vehicle during a crash. As has already been described in a wide range of literature on the subject, in a certain sense, these two test methods involve evaluating mutually contradictory phenomena. This is an extremely serious and difficult problem for automobile development

engineers who are attempting to improve crashworthiness. Issues which will be critical in discussions of vehicle crashworthiness in the future are:

- (1) Does each of these evaluation techniques provide methods and criteria which are suitable for increasing vehicle crashworthiness?
- (2) Which of these test methods is useful in developing and evaluating a vehicle?

A variety of configurations and conditions have been proposed, especially for offset crashes, so further research and discussion are needed.

An area which is currently a main focus of concern is the types of considerations that are needed for vehicle designs which will provide compatible crashworthiness for both small cars and large cars. This issue is especially important for vehicles which are evaluated with these methods.

This research seeks to verify how crash test methods, either full frontal or offset frontal crashes, are associated with actual accidents. This research also discusses what needs to be done in the future.

## BACKGROUND

Among actual accidents, deaths of passengers riding in vehicles may be classified as shown in Figure 1 for Japan and the U.S.

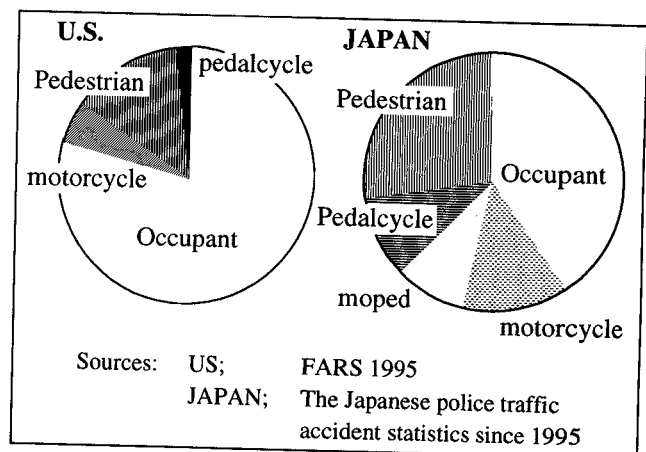
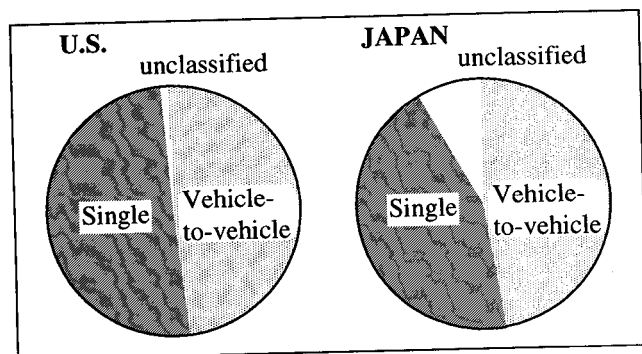


Figure 1. Fatalities in traffic accidents

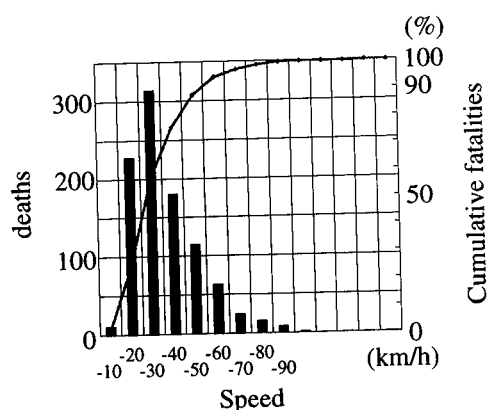
Fatalities of passengers riding in vehicles may be further categorized by the type of accident. There are two general classifications: single-vehicle accidents and vehicle-to-vehicle accidents. The breakdowns for these classifications are shown in Figure 2. As shown in the figures, about half of the accidents are single-vehicle accidents and the other half are vehicle-to-vehicle accidents.



**Figure 2. Classification of fatal collisions**

Figure 3 presents the numbers of cumulative fatalities and the corresponding barrier equivalent speeds.

Approximately 90% of the cumulative fatalities occur at speeds of 50-55km/h or less.















Source: NASS CDS 1991-1995  
head on collisions with belted

**Figure 3. Barrier equivalent speed**

The conditions for the tests currently being conducted were established based on such information.

We will now consider which types of actual accidents each of the test methods is applicable to. The discussion will be simplified in order to maintain a comprehensive focus on current problems and future trends. For further information on the detailed verifications, the reader is referred to the results of research conducted by various

**Table 1. Test configurations**

	JAPAN	U.S.	EUROPE	AUSTRALIA
Regulation	Full flat  50km/h	Full flat  48km/h R/L 0°~30°  48km/h	ODB  56km/h	Full flat  48km/h
Consumer safety information test	Full flat  55km/h	Full flat  56km/h  ODB  64km/h	ORB  55km/h ODB  64km/h	Full flat  56km/h  ODB  64km/h

researchers in the course of establishing each of the crash test methods. The frontal crash test methods which are currently used in Japan, the U.S., Canada, Europe, and Australia are listed in Table 1.

The common types of full frontal crash tests into a flat, rigid barrier, are the regulation tests used by the NHTSA in the U.S., Transport Canada in Canada, the Federal Office of Road Safety (FORS) in Australia, and the Ministry of Transport in Japan. This same type of test is also used in the New Car Assessment Program (NCAP), which serves to provide consumer safety information and incorporates some changes (e.g., a higher crash speed). These test methods will now be considered in relation to actual accidents. In vehicle-to-vehicle accidents, vehicles of the same weight may collide head on with almost no offset. In single-vehicle accidents, the vehicle may collide head-on into an object such as a structure. In actual accidents where the vehicle collides into a structure, vehicles may collide into trees, utility poles, or experience under-ride impact into trucks in addition to colliding into flat objects. At the present time it is very difficult to narrow down correlation with macro data. It is difficult to postulate the exact extent to which this test method covers actual accidents. However, it is possible to infer from the statistics on cumulative fatalities that there are cases in which passengers are subjected to rather strong impacts during collisions.

In light of such considerations, the full frontal rigid barrier crash test methods seem extremely useful for evaluating life saving capabilities which would reduce passenger injuries during extremely strong actual impacts. This test method is advantageous in that it allows evaluations

under conditions in which driver and passenger impact severities are nearly identical. The offset crash tests conducted in the past few years may be broadly divided between offset rigid barrier (ORB) crash tests and offset deformable barrier (ODB) crash tests.

In the case of offset rigid crashes, offset crashes between vehicles of the same weight during vehicle-to-vehicle accidents and offset crashes into structures during single-vehicle accidents are covered by this method and are considered applicable. However, as in the case of full frontal crashes, there is not a clear association between offset rigid crashes and collisions into trees or utility poles, or under-ride impact into trucks.

In the case of offset deformable crashes, the results of experiments replicating vehicle-to-vehicle accidents have been used to establish test conditions, such as collision speed and the specifications of the honeycomb (a deformable device), as has been referred to in European Experimental Vehicle Committee (EEVC) and Insurance Institute of Highway Safety (IIHS) research reports. However, there has been little in the way of verification under conditions in which the vehicles involved have different weights. Therefore, in this study we would like to compare the results of such offset deformable crashes with the results of vehicle-to-vehicle tests based on vehicles with different weights. The need for verification using offset crash tests is to determine how well passenger space in the vehicle cabin is protected. This test serves to evaluate cabin deformation, and resistance to intrusion as a result of the collision. Thus, this method can be used to verify how well the cabin and frame in the engine room compartment are able to absorb the impact energy from the collision and distribute the impact forces. As reported in the for EEVC and IIHS research reports, the specifications of the offset deformable barrier (honeycomb) which is used with this test simulates the stiffness of the structure at the front of a vehicle of nearly average weight (normally called a mid-size vehicle). In terms of actual vehicle-to-vehicle accidents, this test seems to simulate vehicle-to-vehicle collisions involving vehicles of average weight or less.

## TEST RESULTS

Actual vehicle crash tests were conducted under these offset conditions. Figure 4 illustrates the vehicle deformation results of offset rigid collisions. The offset rigid crash test method (ORB) was used by Auto Motor Sport, a German magazine. Figure 5 illustrates the vehicle deformation results of offset deformable collisions.

Figure 6 compares the deformation results of vehicle-to-vehicle offset crash tests in which both vehicles weighed approximately 1500kg. The vehicle-to-vehicle crash test conditions were a speed of 56km/h for both vehicles and an offset of 50%

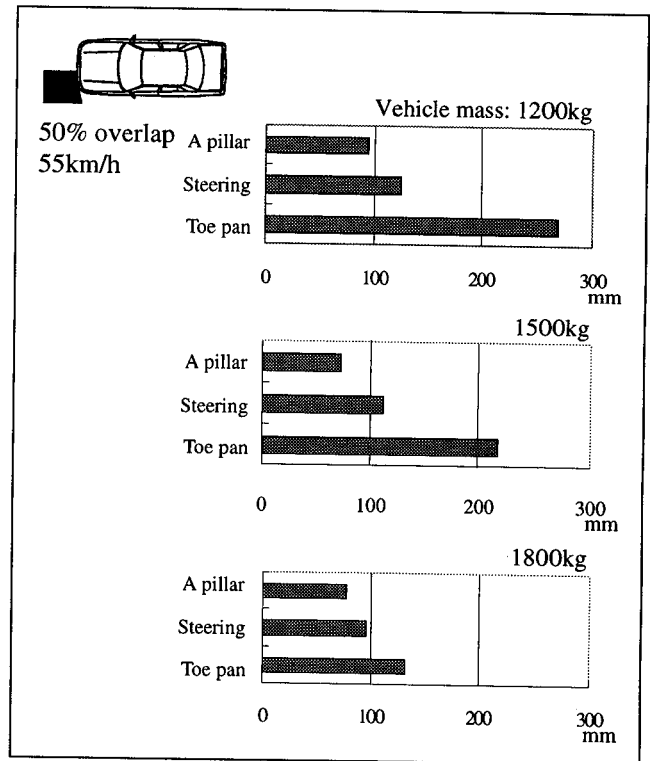


Figure 4. Vehicle deformation (ORB)

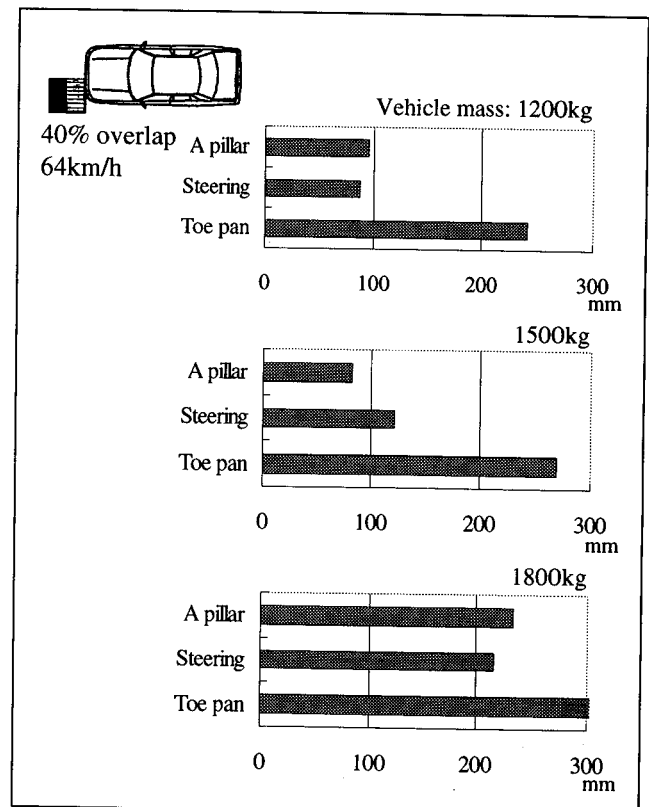
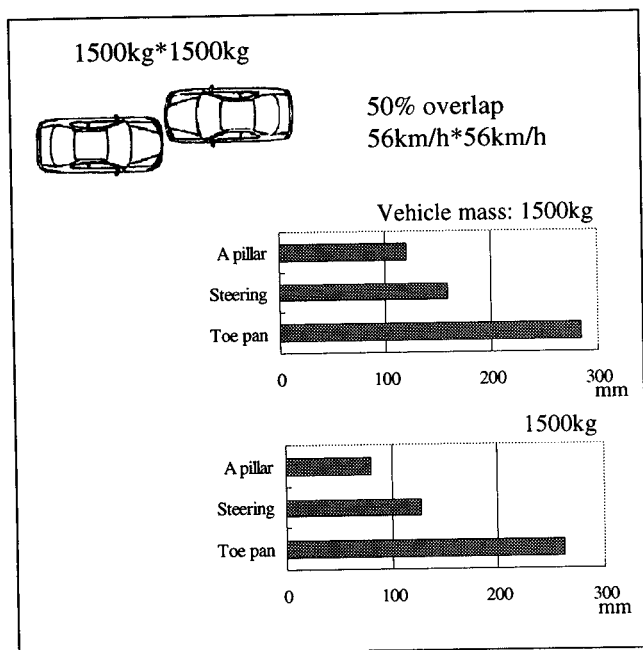
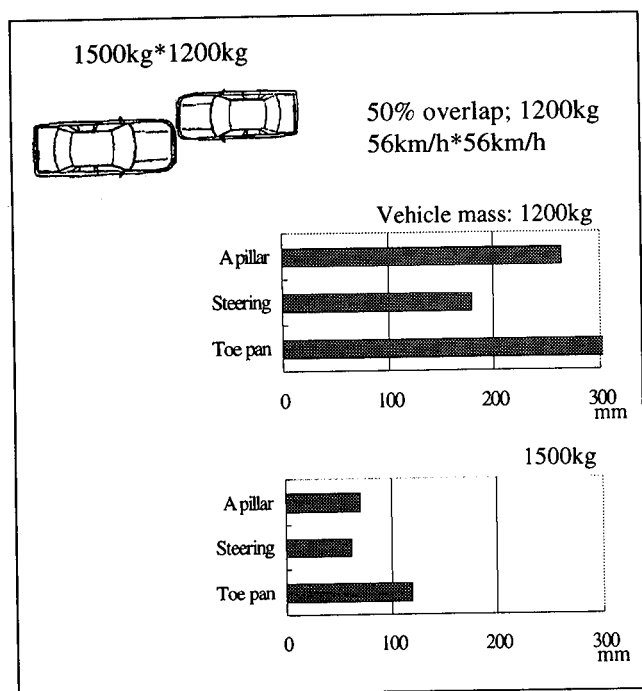


Figure 5. Vehicle deformation (ODB)



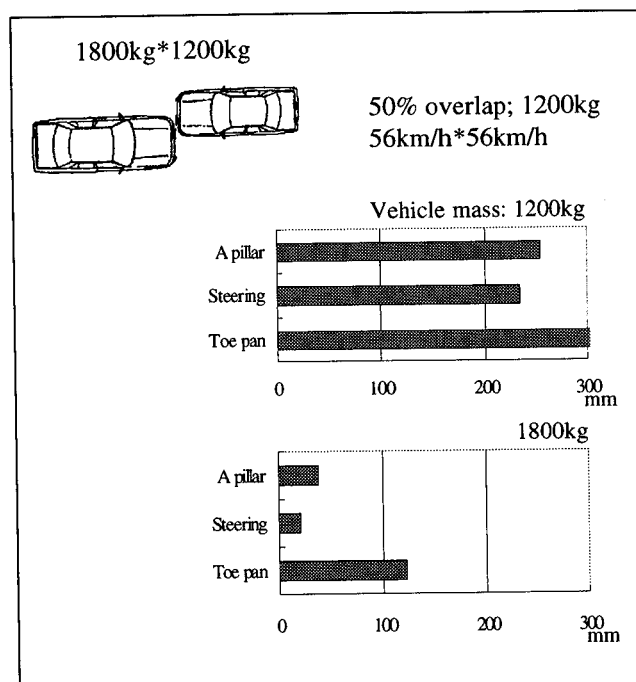
**Figure 6. Vehicle deformation (vehicle-to-vehicle)**



**Figure 7. Vehicle deformation (vehicle-to-vehicle)**

Figure 7 compares the deformation results of the same type of vehicle-to-vehicle offset crash tests in which one of the vehicles weighed approximately 1200kg, and the other approximately 1500kg.

Figure 8 compares the deformation results of the same type of vehicle-to-vehicle offset crash tests in which one of the vehicles weighed approximately 1200kg, and the other approximately 1800kg.



**Figure 8. Vehicle deformation (vehicle-to-vehicle)**

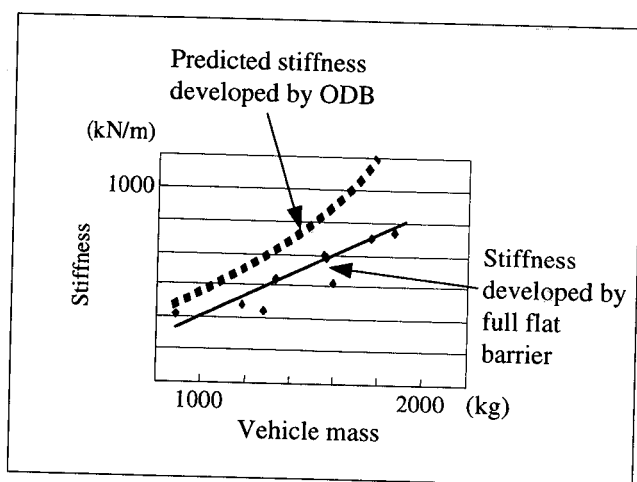
## ANALYSIS

As illustrated above, the results for vehicle-to-vehicle offset crash tests in which both vehicles weighed approximately 1500kg were consistent with the offset deformable crash test results. When the vehicles had different weights, there is a significant difference between the vehicle-to-vehicle crash test results and the barrier crash test results.

As mentioned above, offset rigid barrier collisions simulate collisions between vehicles of the same weight, or collisions into structures. In contrast, offset deformable barrier collisions are essentially offset collisions between vehicles of average weight. However, the results of the offset deformable barrier crash tests indicate that if the colliding vehicle weighs more than average, (e.g., 1800kg) a bottoming out phenomenon will occur due to the characteristics of the deformable barrier (i.e., the honeycomb). As a result it would seem that an actual vehicle-to-vehicle crash is not simulated in such cases. Similar problems have already been pointed out among researchers; this will remain a topic for future study.

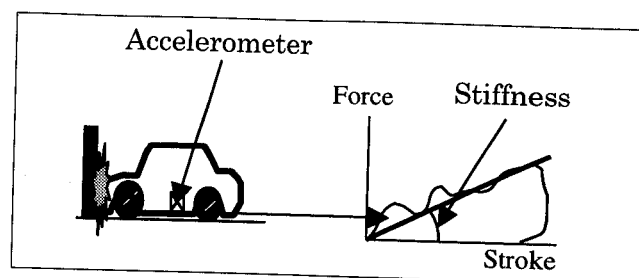
Nonetheless, this cannot be set aside as a simple "issue". In other words, vehicles which are developed in order to obtain good evaluation results using such test methods may create a number of problems under actual road conditions.

One such problem is an increase in vehicle weight. It is inevitable that weights will increase as a result of improvements in crashworthiness. Unfortunately, excessive increases in vehicle weight remain a significant problem. Specifically, vehicles whose structures are designed based on test conditions and evaluation criteria which are significantly different from actual accident conditions will not contribute appropriately to efforts to improve crashworthiness under actual road conditions. Also this is a problem of compatibility in vehicle-to-vehicle crashes. Along with the need to protect the vehicle of a person driving in mixed traffic, it is also necessary to protect the other vehicle in an accident. This capability may be an important issue in the future. Among actual accidents, total fatalities are divided approximately evenly between single-vehicle accidents and vehicle-to-vehicle accidents. It is necessary to protect passengers in both of these types of accidents. In particular, during vehicle-to-vehicle collisions, it is necessary to consider the safety of the other driver -- not just the driver in the car which is being designed. Results from the vehicle-to-vehicle crashes of different weights specifically show this problem. Figure 9 illustrates this phenomenon graphically. As vehicle weight increases, the stiffness of the vehicle front increases.



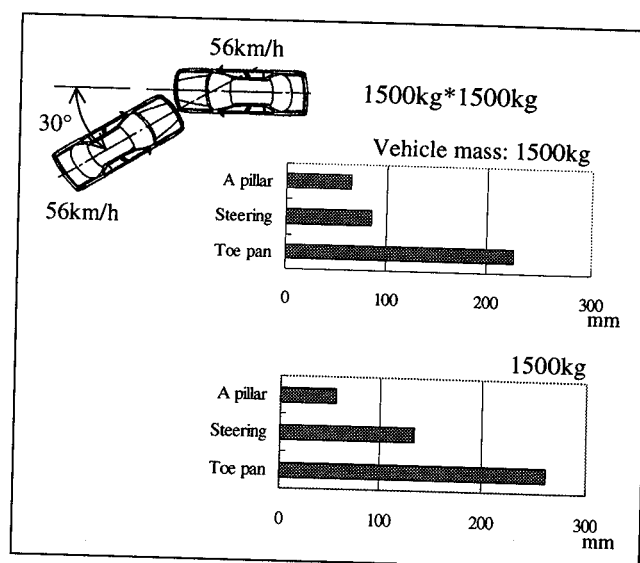
**Figure 9. Prediction of stiffness**

The test results done on each vehicle in the U.S. with an NCAP full frontal barrier show a strong correlation between vehicle weight and stiffness. In other words, an increase in vehicle weight can be inferred to lead to an increase in aggressiveness toward the other vehicle. As used here, the term 'vehicle stiffness' is defined as the slope of the load on the chassis as derived from an accelerometer attached to the cabin floor on the chassis. Figure 10.



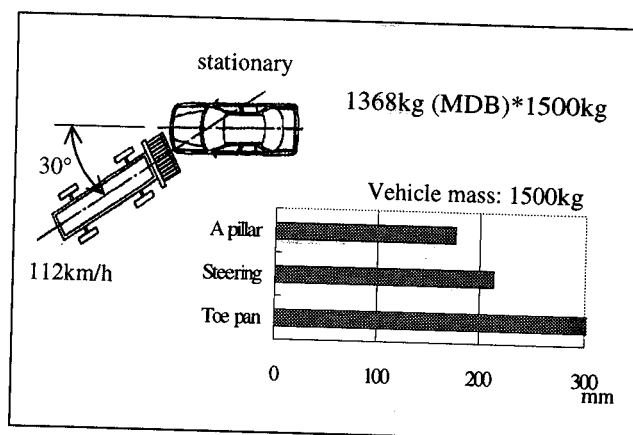
**Figure 10. Definition of vehicle stiffness**

Next we used same-weight vehicles as described above to verify the recent test method of the U.S. NHTSA, which is being researched based on vehicle-to-vehicle crashes. The 56km/h vehicle-to-vehicle crash results are shown in Figure 11.



**Figure 11. Vehicle deformation (vehicle-to-vehicle)**

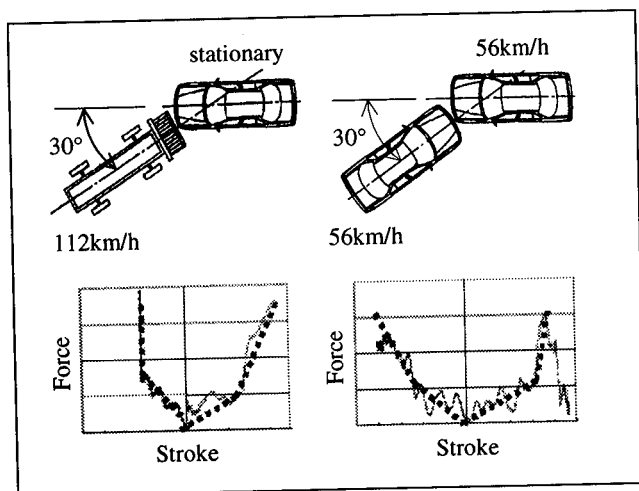
Figure 12 illustrates the results of a stationary vehicle crash test using a 112km/h moving deformable barrier (MDB).



**Figure 12. Vehicle deformation (vehicle-to-vehicle)**

As indicated by the diagram, this test method clearly involves a vehicle-to-vehicle type of accident. One way it is different from the frontal offset crashes discussed thus far is that the offset is oblique. The second is to use an MDB. The MDB weighs 1368kg, which is the average vehicle weight in the U.S. This method appears to be based on the type of accident which is likely to occur frequently under actual road conditions. Note that the NHTSA research results should be checked for details regarding what types of actual accident situations are covered. As illustrated in Figures 11 and 12, a comparison of deformation amounts in the vehicle which is collided into shows that deformation for MDB and a vehicle is much greater than deformation between one vehicle and another.

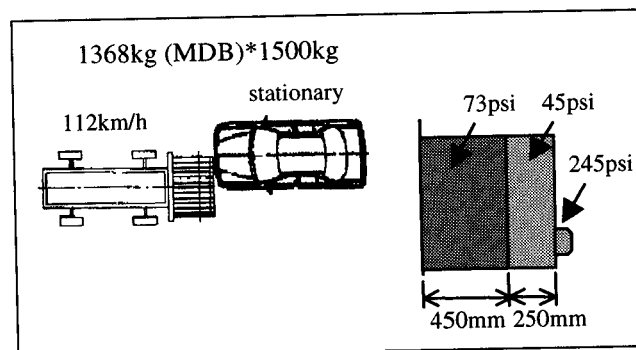
One reason for this can be clarified by comparing the amount of deformation in the deformed area on the colliding vehicle. This comparison shows that there are problems in the characteristics of the barrier, i.e., the honeycomb, similar to the results for the offset deformable crash tests. As in the EEVC and IIHS tests, this problem seems to be due to honeycomb bottoming out, i.e., the stroke is significantly different than that of actual vehicles. Figure 13 illustrates the force (deceleration) vs. displacement characteristic in an actual vehicle compared to the results obtained in a test using a honeycomb.



**Figure 13. Comparison of Force-Stroke characteristics**

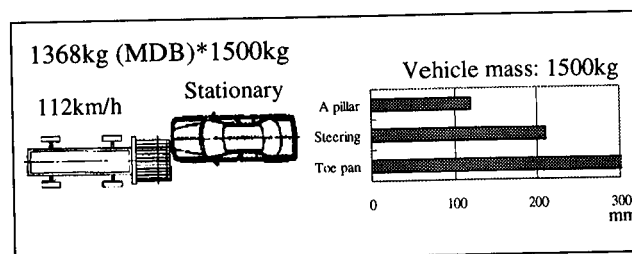
Figure 13 also indicates a clear difference between the results. Assuming the collision speed simulation parameter is physically and theoretically correct, the honeycomb characteristics are a definite problem with this test method. This test method has other problems as well: reproducibility and practicality. Since this test method involves an oblique crash test, there is inconsistency in the amount of offset. And it is almost impossible to conduct the high MDB test speed in an ordinary indoor laboratory, so it is not well suited to third-party evaluation tests, including compliance. Then

a test method which would theoretically solve the problems discussed above was devised. This test method, illustrated in Figure 14, was developed with consideration for reasonableness, faithfulness, reproducibility, practicality, and aggressiveness evaluations.



**Figure 14. Test method of MDB-to-vehicle**

Like NHTSA, for the MDB we selected the average weight which was most likely to be encountered under actual road conditions. We tried using a compound honeycomb consisting of a honeycomb which is average or has a hardness that is nearly the same as the stiffness of the engine rooms of vehicles which are commonly sold in the U.S., plus a honeycomb with stiffness characteristics similar to cabin stiffness. A relative MDB speed between 100km/h and 120km/h would simulate vehicle-to-vehicle collision speed of approximately 56km/h. In this test we used a speed of 112km/h. In order to minimize inconsistency in the data caused by the test method, we decided to make the collided vehicle stationary in a frontal offset collision. Some evaluations may consider an oblique collision to have a better correlation to actual road conditions, but oblique collisions were not used in this test. The test results are shown in Figure 15.



**Figure 15. Vehicle deformation (MDB-to-vehicle)**

The vehicle deformation approaches the test results in Figure 15, but the amount of deformation for the steering wheel is still larger. This seems to be due to the fact that the MDB rose onto the collided vehicle. There are two further problems with this test method. One is that it does not solve the difficulty of conducting the test in an ordinary indoor laboratory. The second problem is that the use of a compound honeycomb comprising two different honeycomb types makes it necessary to verify whether the method is acceptable in terms of production technology (including reproducibility), and whether the desired characteristics can be obtained.

## CONCLUSION

The offset deformable barrier tests currently conducted using honeycombs are suitable for evaluating vehicle safety in vehicle-to-vehicle accidents involving vehicles which weigh approximately 1500kg or less. However, the results are not necessarily consistent with actual accidents in cases where the vehicles weigh more than approximately 1500kg. This is due to a problem with the specifications of the honeycomb, which is the deformable device. Specifically, the force-stroke characteristic of currently used honeycombs is not suitable for vehicle-to-vehicle crash tests with vehicle weights of 1500kg or greater. Our results reconfirm the recognition and observation by others that this is a bottoming out problem. In addition, it was learned that vehicle-to-vehicle offset collisions involving an MDB are not necessarily consistent with actual accidents in terms of what actually happens (e.g., the MDB rises onto the test car). Therefore further research is needed.

## DISCUSSION

As described above, test methods involving deformable barriers have been proposed and are used to simulate vehicle to vehicle accidents. However, based on these tests results, the barrier characteristics do not always seem to replicate actual accidents. In cases where there is a difference in weight between vehicles, as is commonly found in vehicle-to-vehicle accidents, the heavier vehicle will suffer less deformation than the lighter vehicle. This has been confirmed experimentally, so test methods which provide different results are clearly problematic in a number of respects. Specifically, there is the problem of the collision speed, which is not related to the vehicle weights, and the related honeycomb characteristics. In the future we believe it will be necessary to establish appropriate test methods based on further research.

Another problem which may arise is that vehicles which are developed using such problematic test methods may not be suitable in terms of compatibility in vehicle to vehicle collisions -- an issue which is expected to be important in

the future. In particular, heavier than average vehicles which are sold in each market have the potential to increase aggressiveness toward small and lighter-weight vehicles.

This paper presents research on vehicle to vehicle tests involving an MDB, and compares these tests to ODB crash tests which are currently used. Further research will be needed in the future on criteria for evaluating vehicle aggressiveness.

Collision accidents are extremely complex. For this reason, it is necessary to have a number of methods for evaluating crashworthiness -- not just one method. In particular, it is impossible to use a single test method to evaluate mutually contradictory phenomena (i.e., single vehicle crash protection evaluations and securing cabin space in vehicle-to-vehicle crashes). Therefore, care must be taken in publishing test results supposedly serving as safety information.

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# FRONTAL IMPACT PROTECTION: TAILORING SAFETY SYSTEM PERFORMANCE BY THE PREDICTION OF DRIVER SIZE AND SEATED POSITION

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Paper Number 98-S1-O-09

## ABSTRACT

The design of systems to protect occupants in car crashes assume that the size and seated position of the driver is 'average'. If the occupant protection system had information that the driver is larger or smaller than 'average', sitting closer to or further from the steering wheel, the system could tailor its performance and enhance the protection offered. In this study measurements of anthropometric characteristics of drivers and their position were taken and analyses carried out to identify correlations between the measures. It is possible to predict a driver's physical dimensions and seated position from these data. The algorithms provided an input to the determination of the physical characteristics of the driver and their seated position in relation to the steering wheel, from sensors in the seat and seat mounting.

## INTRODUCTION

There is considerable potential for improving occupant protection in crashes by the application of smart systems technology. Galer and Jones (1994a) describe a number of ways in which intelligent secondary safety systems can be developed, and provide indications of which strategies would be preferable from a design perspective. Intelligent systems technology can effectively be applied in three main areas in secondary safety. These are providing information on the characteristics of the environment in which the system is operating i.e. the vehicle, the occupant and the crash; interpreting that information to provide appropriate occupant protection; and the initiation of that protection via actuators. The intelligent system can gather relevant data, interpret it, tailor and initiate a response which optimises the protection of the occupant.

At present a seatbelt or airbag will perform in a crash irrespective of the size of the occupant or their proximity to the steering wheel. If information about the occupant such as this could be made available to an occupant protection system via sensors in the seat and its mountings, it would be possible to make the seatbelt or airbag operate in a way that is tailored to the characteristics of that particular occupant. For example, the airbag could deploy more quickly if the occupant is short, (positional information from sensors in the seat runners) who will be sitting closer to the steering wheel

and currently runs the risk of hitting a deploying airbag. The intelligence is now available to make decisions about how an adaptable system should be deployed (Galer and Jones, 1994b). Smith, Bergfried and Faye's paper (1994) concerning their SMART<sup>TM</sup> Airbag System provides information about system optimisation and how algorithms could be developed for an adaptive system if data about occupant size, position, crash severity and ambient conditions were known. Schulte and Weyersberg (1994) describe ways in which smart seatbelts could help provide optimal impact protection for a wider range of individuals than at present.

The seated position adopted by car drivers depends on their physical characteristics, the adjustability options provided by the vehicle package and, to some extent, personal preference. Drivers must maintain proper control of the vehicle, so they need to be able to reach the pedals, gear selector, steering wheel and other controls; they must also be able to see out of the vehicle in the forward, side and rear view. In order to achieve a seated position that enables the driver to undertake these activities the vehicle package offers a range of adjustments. Primarily, these are fore and aft movement of the seat and seat back rake angle. The driver has the opportunity to adjust these variables until an acceptable driving position is attained. When a vehicle is involved in a crash the injury outcome to the occupants will depend principally on the direction and energy of the impact. However, also of importance is the amount of space the occupants have to move in before the safety system, the vehicle interior or intruding objects are contacted. In the case of drivers involved in frontal impacts their position in relation to the steering wheel is a key element in the nature and severity of injuries they receive (Aibe, Watanabe, Okamoto and Nakamori, 1982; Hyde, 1992). The performance of the seatbelt and airbag will also have a major effect on the nature and severity of injuries. The main purpose of the seat belt is to slow down the occupant and absorb the energy of the crash. The purpose of the Euro-sized airbag is to absorb the energy of the head as it is about to strike the steering wheel, thus reducing facial injuries. The interaction between the occupant and the safety system is critically dependent on the size of the occupant and their proximity to the steering wheel.

Developments such as retractors and webbing grabbers have improved the performance of seatbelts. Seatbelt reel and buckle pre-tensioners pull the seatbelt



tightly round the occupant when a frontal crash is detected. This reduces slack in the belt, couples the occupant into the crash and reduces the energy of the impact with the belt. The airbag deploys very rapidly and with a great deal of energy, then gradually deflates through vents in the rear. It is important, therefore, that the occupant does not hit the airbag while it is deploying, nor hit it too late when deflation is occurring. Until recently the deployment characteristics of airbags were fixed, however, further developments in technology have made it possible to adjust the performance of airbags in car crashes. For example, the airbag inflators can have variable deployment time, maximum inflation pressures and gas flow rates (Galer, 1993). This capability, together with the availability of microprocessor based control systems, has made it possible to provide the intelligence needed to make decisions about how an adaptable system should be deployed to more closely meet the requirements of the individual occupant.

This research programme was concerned with finding means to provide an adaptable secondary safety system with information about the physical characteristics of the vehicle occupants, specifically the driver, such as their size and position in relation to the interior of the vehicle. With this information the secondary safety system could respond according to whether the occupant was, for example, large or small, sitting close to or further away from the steering wheel.

## RESEARCH RATIONALE

It can be seen that there could well be benefits in terms of injury reduction to be able to tailor the performance of the safety system to the physical characteristics of the occupant and/or to their seated position. The issue addressed in this paper is how to obtain the necessary information on occupant size and seated position. The latter option of gathering the information from sensors in the vehicle seat and its mountings was chosen for a number of reasons including reliability, cost and nearness to likely market implementation.

The two elements to be identified, therefore, are occupant size and proximity to the steering wheel (seated position). The research programme measured certain key anthropometric dimensions of drivers, their position in the vehicle and in relation to the steering wheel, and analysed the data to identify correlations. Algorithms were then established. A seat and its mountings were instrumented with sensors and trials undertaken with drivers to investigate whether the algorithms were correct and whether occupant size and/or seated position could be established from such sensors. This work is reported in more detail in Grafton, Galer Flyte, King and Jackson, 1995.

## Aims of the Research

1. To investigate which vehicle-related measures can be used reliably to classify and categorise drivers according to their size and seated position in the vehicle.
2. To investigate what vehicle-related measures can be used reliably to locate drivers with respect to injury producing features such as the steering wheel.
3. To make recommendations from significant relationships as to which seat variables could be used to categorise drivers and their seated position, and so be used for the formulation of algorithms.
4. To investigate the feasibility of using smart sensor technology to obtain information about the characteristics of the occupant with which to tailor the performance of the vehicle occupant protection systems. The information about the occupant would come from sensors in the seat and its mountings.
5. To build and test a technology demonstrator of a 'Smart Seat'.

## Research Strategy

The research involved a number of experimental approaches.

**Anthropometric Studies:** Measurements were taken of members of the driving public to record their anthropometric characteristics and the seated position they adopted in their own vehicle. Significant correlations between vehicle-related and occupant-related measures were identified and algorithms established (Perchard, 1994). These algorithms were tested in trials with drivers in the technology demonstrator.

**MADYMO Modelling:** Investigations with MADYMO were undertaken to show whether improvements could be made to the performance of an existing safety system if the safety designer could assume that the size and the position of the occupant were known prior to the final design of the system. The outcome of the investigations was expected to be a broad 'yes' or 'no' answer to the above question and an indication of how extensively an existing safety system would have to be changed to make it adaptable. This is reported in Galer Flyte and Grafton, 1997.

**Instrumentation Exercise:** An instrumentation exercise was also undertaken to identify the ways in which a seat could be made smarter to provide the information required to position and classify occupants. Sensors and other instrumentation were fitted to a vehicle seat and the fundamental design work was undertaken in the laboratory.

**Construction And Testing Of A Technology Demonstrator:** A technology demonstrator was created to verify the operation and usefulness of the occupant position sensing and to validate the findings of the study on the prediction of occupant size and seating position from vehicle related parameters. Verification of the

system's reliability, repeatability and immunity to error was undertaken by conducting trials with drivers of known anthropometric characteristics.

## ANTHROPOMETRIC STUDIES

A study of the anthropometry of British car drivers was conducted by Haslegrave in 1980, and although the study was extensive it measured only the drivers and did not include their seated position in the vehicle. Parkin, Mackay and Cooper (1993) undertook a study to relate drivers' seated position to the positions specified for dummies in crash tests. Their research found that drivers do not necessarily sit in the positions dummies are placed for crash testing, and that the discrepancies can be large. For example, they calculated that a 5th percentile female actually sits up to 9.2 cm further forward than would be expected on the basis of the dummy position requirements. The measures were taken from video recordings of drivers in moving cars. Although there are a number of studies concerned with occupant size, posture and comfort these do not provide the vehicle-related information required for this study. This study, therefore, measured driver related factors, vehicle related factors, and driver-vehicle interaction related factors with a view to finding the minimum number of measures needed to categorise the driver reliably in terms of size and seat position. This work is reported in more detail in Perchard, 1994.

Measurements were taken of the drivers, the vehicles and the driver-vehicle interaction as described below.

### Measurements Of The Drivers

Stature  
Leg length (top of greater trochanter to floor by heel)  
Chest/bust circumference  
Waist circumference  
Hip circumference  
Weight (st. lb.)  
Trunk length was computed from stature and leg length, and age was also recorded.

### Measurements Of The Vehicles

Runner on door sill to top of steering wheel (vertical)  
Runner on door sill to centre of steering wheel (vertical)  
Runner on door sill to seat back rake fulcrum (vertical)  
Diameter of steering wheel  
Base of 'A' pillar to top of steering wheel  
Base of 'A' pillar to front edge of seat (horizontal)  
Front edge of seat to brake pedal (horizontal)  
Seat length i.e. front of seat edge to seat back rake fulcrum (horizontal)  
Seat back rake angle (in degrees)  
Seatbelt payout (without driver)

## Measurements Of The Driver-Vehicle Interactions

Nasion to top of steering wheel  
Nasion to centre of steering wheel hub  
Nasion to runner on door sill (vertical)  
Sternum/seatbelt junction to top of steering wheel  
Sternum/seatbelt junction to centre of steering wheel hub  
Sternum/seatbelt junction to runner on door sill (vertical)  
Seatbelt payout with driver  
Seatbelt payout difference was calculated from seatbelt payout with and without driver.

### What Vehicle Related Measures Can Be Used To Classify And Categorise Drivers According To Their Size And Seated Position In The Vehicle?

Multiple regression analyses were performed for the vehicle related variables for each of the anthropometric variables. The main findings are summarised below.

**Trunk Length** For males, trunk length can be calculated from the 'A' pillar to seat front distance with a high probability of accuracy.

No reliable way of predicting trunk length for females was found.

**Leg Length** For males, leg length can be calculated from an equation including the door sill to the top of the steering wheel distance, the distance from the seat rake fulcrum to the door sill, the 'A' pillar to seat front, and the seat back rake angle.

No reliable way of predicting leg length for females was found.

**Chest/Bust, Waist And Hip Circumferences** No accurate or reliable way of predicting these circumferences was found.

**Weight** Weight of males can be predicted reliably and with a good degree of accuracy from the brake pedal to seat front distance.

Weight of females can be predicted with a high degree of accuracy and a high level of reliability from the seatbelt payout and the brake pedal to seat front distance.

### What Vehicle Related Measures Can Be Used Reliably To Locate Drivers With Respect To Injury Producing Features Such As The Steering Wheel?

The measures used in the study to locate the driver in relation to injury producing features, 'injury distances', are the distances from the head and chest to the steering wheel.

**Nasion To Top Of Steering Wheel** The nasion to top of steering wheel can be calculated reliably for a combined males and females data set from the door sill to centre of steering wheel distance, seatbelt payout, 'A' pillar to top of steering wheel distance, 'A' pillar to seat front distance, seat back rake angle, and seat length.

**Nasion To Centre Of Steering Wheel** The nasion to centre of steering wheel distance can be calculated with a high degree of accuracy and reliability for a combined males and females data set from the brake pedal to seat front distance, seatbelt payout, 'A' pillar to seat front distance, and seat back rake angle.

**Sternum To Top Of Steering Wheel** The sternum to top of steering wheel distance can be calculated for a combined male/female data set from the brake distance to seat front distance, door sill to centre of steering wheel distance, seatbelt payout, seat rake angle, 'A' pillar to seat front distance, and 'A' pillar to top of steering wheel distance.

**Sternum To Centre Of Steering Wheel** The combined male/female data set reliably predicts the sternum to centre of steering wheel distance to a very high degree of accuracy. This is calculated from seat rake angle, 'A' pillar to seat front distance, seatbelt payout, 'A' pillar to top of steering wheel distance, seat fulcrum to door sill distance, door sill to centre of steering wheel, and door sill to top of steering wheel distances.

## CONSTRUCTION AND TESTING OF THE 'SMART SEAT' TECHNOLOGY DEMONSTRATOR

Construction of the technology demonstrator consisted of fitting the instrumented seat and seatbelt into a Rover 400 vehicle buck. The system components were integrated into the vehicle buck, the system calibrated and trials run to see how accurately the seat position measures related to actual occupant position. The technology demonstrator instrumented seat provided data from sensors with which to locate the occupant in the vehicle and classify them into broad size categories. The drivers and their position in the vehicle were measured and these actual measurements compared with the measures provided by the sensors in the 'smart seat' installed in a stationary car buck. Participants of known anthropometric characteristics could then be measured by the system to 'calibrate' it for a particular vehicle. Verification experiments were subsequently carried out on different participants to determine the accuracy of the system output.

The aim of the verification trials was to validate the operation of the 'smart seat' system and sensors by establishing reliable relationships between data from the seat and the occupants' actual size and position with the vehicle. Two types of measurement were taken, those the 'smart seat' system measured directly, for example, seatbelt payout and seat back rake angle, and those that needed to be calculated, for example, sternum to steering wheel distance. Table 1 shows the measurements taken in the trials.

Anthropometric measurements were taken to record the size and shape of persons taking part in the study. The occupant was located relative to the interior of the

Table 1.  
Measurements Taken During The Verification Trials

Calculated variables	Measured variables
Stature	Seat fore / aft
Leg length	Seat height
Weight	Seat back rake angle
Sternum to centre of driving wheel	Head position sensor output
Nasion to centre of driving wheel	Seatbelt payout without driver
	Seatbelt payout with driver

vehicle by measuring from the centre of the steering wheel to their nasion and to the point where the seatbelt crossed their sternum. These two distances are critical for the safety system. Measures of the seat position, seatbelt payout and the distance of the occupant's head from the head restraint were taken automatically by the computer and a graphical display on the computer screen showed where they were sitting.

Multiple regression analysis compared each factor to be calculated against all of the factors that could be measured. An overview of the results is shown in Figure 1 below. The size of the dot in each box indicates how well each measured variable predicts each calculated variable. No dot indicates the correlation is poor or non-existent. An example of this would be that the two variables that predict height are the seat fore/aft position and the back rake angle. Of the two predictors, the fore/aft position is strong and the rake angle is weak.

	Fore / Aft	Up / Down	Head - Rest	Belt Payout	Rake Angle
Leg length	●				
Height	●				●
Weight	●			●	●
Sternum - Wheel	●			●	●
Nasion - Wheel	●		●		●

Figure 1. Prediction matrix used in analysis of data.

The strongest relationships from the 'smart seat' sensing system can be seen in Figure 1. The sternum to steering wheel distance and nasion to steering wheel distance are strongly predicted by the three factors that can be measured.

## DISCUSSION

Driving is a dynamic activity and the position of the driver varies continually. The method used to obtain data on seated position took measurements of a static driver in a static car. The seat position adjustments, however, were reliable as the participants had driven their own cars to the test site and had not subsequently altered the adjustments. The variation, therefore, was only in the more subtle movements of head and chest position in relation to the steering wheel, both of which vary continuously during driving. Hence any variations for individuals would be small if the seat adjustments remained the same. There are also boundaries in that drivers cannot sit further away from the steering wheel than the measures taken in this study, as they are constrained by the seat back and the head restraint. They may only sit or move closer to the steering wheel by leaning forward. This was addressed by the seat back/head restraint mounted sensors (Grafton et al., 1995) developed later in the programme. The results were compared with those found in Parkin et al. (1993) but could only be made for the direct 'nasion to centre of steering wheel' measure. Only an approximate fit was possible, however, the variation in distance was not greater than 2 cm or 3.4% which occurs at the 95th percentile level. This indicates that the results of this study are supported by Parkin et al. (1993) where the sample size was 1000 and where the measurements were determined from videos of drivers who were unaware of the camera in the dynamic, real life situation of driving a vehicle.

The study did not attempt to obtain exact measures of each individual driver but measures that would enable the drivers and their seated position to be classified into broad bands that would, in turn, facilitate some tailoring of the occupant protection system. It is sufficient at this stage of technological development that the system knows that the driver falls outside the 'normal' seated position of the 50th percentile male for which the systems are primarily designed.

It was not easy to deduce logically or reliably the predictor variables through the simple association of one variable with another, hence stepwise regression analysis was implemented in order to obtain reliable and accurate results. It was also difficult to predict all the variables that would have a significant influence in the results and it is possible that not all the useful variables have been included in the analysis.

The low sample size has undoubtedly introduced errors, but as sound relationships were found for a small

population they will only improve as the sample size increases and the distribution normalises.

For the data to be considered valid for a range of vehicle types, the investigations would have to be carried out on a number of different vehicles. One reason for the strength of the correlations between factors in this experiment is that the vehicle type was the same throughout the investigation.

However, it appears possible to use a seat based sensor system to measure and predict the position of the occupant relative to the interior of the vehicle if the occupant adopted a normal driving posture. It is also possible, but with less accuracy, to give an indication of the occupant's physical size characteristics.

The results are highly vehicle specific but it seems probable that relationships similar to those identified during this study will exist for other vehicle types.

## CONCLUSIONS

There is an opportunity to enhance the performance of current secondary safety systems in frontal collisions by tailoring the performance to the characteristics of the driver.

Algorithms have been established which enable the prediction of occupant size and seated position.

Certain critical characteristics and dimensions can be measured and/or calculated from data obtained from the seat and seatbelt configuration.

Sensors have been implemented in a prototype Smart Seat that predict the physical characteristics of the seat occupant and their location with regard to critical vehicle features such as the steering wheel.

This is a very exciting and forward looking research activity.

## ACKNOWLEDGEMENTS

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# SIMULATION OF FOOT WELL INTRUSION FOR SLED TESTING

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## ABSTRACT

There is a high risk of the lower extremities being injured in frontal crashes of passenger cars. Head and chest are well protected nowadays due to safety features like airbags, seat belts and absorbing materials in the interior, while only limited safety improvements have been achieved in the leg area.

In order to investigate the injury mechanism of lower legs, to define development targets and for the assessment of safety devices, PARS developed a tool to reproduce the measured dynamic crash intrusion of the foot well in static and in sled tests. This foot well intrusion system (patent pending) allows the adjustment of both movements of the firewall, parallel intrusion and rotation effects, nearly independent and in a wide range.

In this paper the functioning principle of this device will be presented. A comparison between real crash tests and experimental simulations with sled tests will be reviewed.

## INTRODUCTION

The evaluation of several accident statistics point out, that the lower extremities are the second most endangered body region in frontal crashes. Only the head area is injured more often. The Goal of PARS was to develop a cost effective and reproducible testing tool for further research on protection devices for lower extremities. This goal was met by a mechanical foot well intrusion system for static laboratory testing and also for sled testing on an impact or a reverse sled. To receive the required data for initialization of the intrusion system there is only one baseline crash necessary. Expensive crash testing can be avoided by using this system without any loss of information. Development of new protection systems for legs and feet can be carried out faster and more effectively. Further major advantages are the easy assembly, the low production and operating costs and the universal use (e.g. steering column intrusion, etc.).

## KINEMATICS OF FOOT WELL INTRUSION IN CRASHES

Through extensive analysis of static and dynamic deformation data the principle kinematics of the foot well were discovered. Mainly the following two movements were found out (Fig.1.): on one hand a rotation of the firewall around y-axis and on the other hand a translation of the foot well in direction of the x-axis.

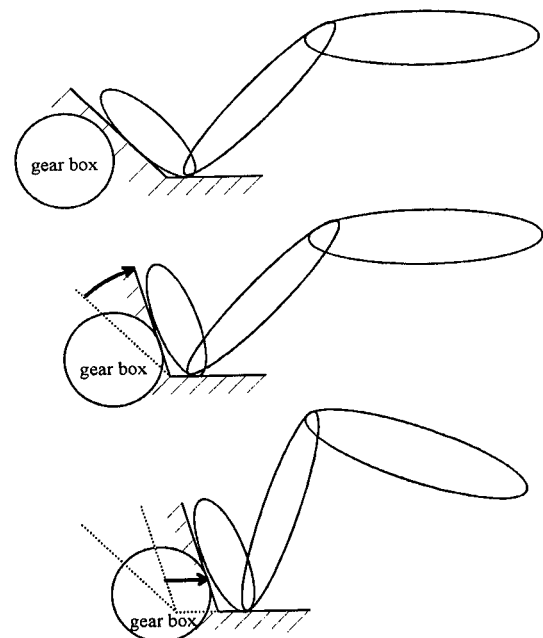


Figure 1. Principle of foot well intrusion during crash.

The two movements are not proceeding one after the other but combined. Based on this knowledge, the conditions for the intrusion system were defined. The system has to perform the measured movements and accelerations so that the dummy loads are similar to the crash.

## ASSEMBLY OF THE FOOT WELL INTRUSION SYSTEM

An analysis of the pros and cons of several construction possibilities pointed out that only a system which is independent of the kinetic sled energy will reach the demanded repeatability. For the acceptance of automobile manufacturers it has to be cost effective and reliable. PARS uses a pyrotechnical driving unit for the intrusion system which fulfills both criteria.

The principle assembly of the foot well intrusion system with its major parts is shown in Figure 2.

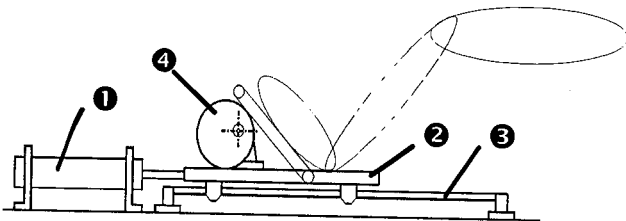


Figure 2. Principle assembly of the foot well intrusion system.

The drive of the system is a pneumatic cylinder ① which is charged by a pyrotechnical unit. The load of the cylinder is applied over a piston rod to the sled ②. The sled is mounted on a shaft ③ so that it is able to perform a linear movement in direction of the x-axis. The rotation of the firewall is realized by a curve disc ④, which is assembled on a splineshaft. A gear drive is the connection between the linear movement and the rotation. At the end of the linear movement a deformation tube absorbs the remaining kinetic energy of the sled and the system is fixed in the reached position. Otherwise the HYGE-sled acceleration would cause a shifting of the intrusion system backwards due to inertia.

## TESTING WITH THE FOOT WELL INTRUSION SYSTEM

The intrusion system can be used in static tests as well as in sledtests. The test setup will be described in the following paragraphs.

### Static laboratory testing

For static laboratory tests the intrusion system will be mounted on a platform or in a body in white (see Fig. 3.). With such an assembly protection devices can be tested and developed as well as analysis about the intrusion of the foot controls can be performed.

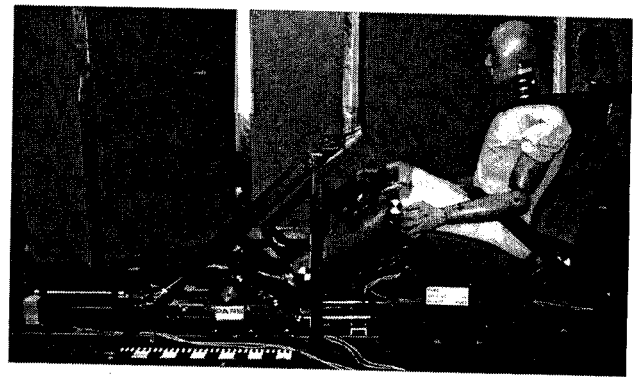


Figure 3. Foot well intrusion system mounted on a platform

### Sled testing

PARS realized multiple sledtests on its HYGE-sled. Therefore the system will be integrated in a body in white (see Fig. 4.). The dummy and the feet have to be placed in the requested position.

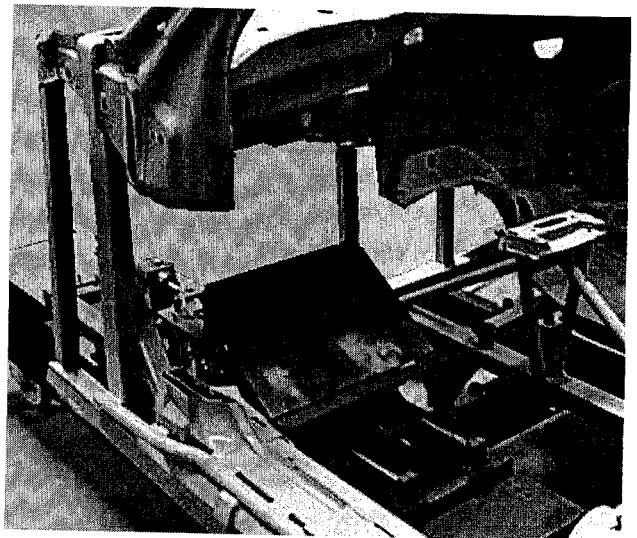


Figure 4. Foot well intrusion system mounted in a sled buck.

The system is actuated by timer ignition independent of the sled pulse. It carries out a combined movement of a linear intrusion and a rotation around y-axis.

### Setup parameters

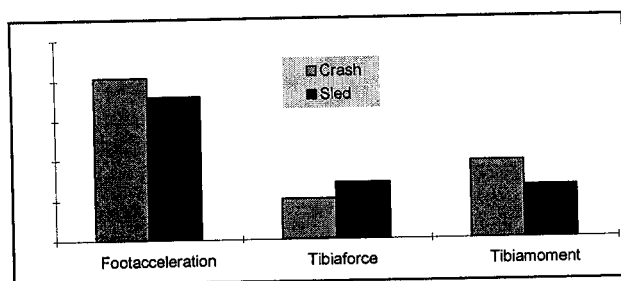
By changing several adjustable parameters the system could be varied in a wide range. So it could be adapted to nearly every kind of intrusion movement in order to represent crash behavior of different cars.

- The relation between the linear movement and the rotation can be changed by a different transmission ratio.
- Curve discs with a geometric cam could be used.
- To achieve different accelerations of the system the charge of the pyrotechnical drive can be changed.
- The movement of the sled can be adjusted from 50 mm to 250 mm with a stopper.
- The position of the firewall before crash can be fixed with a distance holder in an area between 30° and 45°.
- The angle of rotation of the foot panel can be adjusted from 0° to 45°.

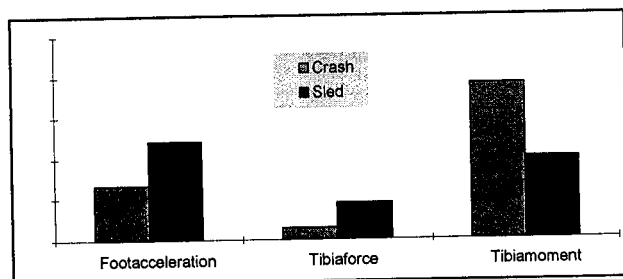
To compare the results of the sledtests with the crash it is necessary to place measurement equipment in a similar position compared to the crash.

### COMPARISON BETWEEN THE RESULTS OF A CRASHTEST AND A SLEDTEST

During a study several crashtests were performed at PARS. A baseline setup for the HYGE-sled was defined by these crashtests. A comparison between the crashtest and the sledtest is shown in Fig. 5. and Fig. 6. The foot acceleration, tibiaforce and tibiamoment are shown representative in the diagram. The left and right foot are presented in separate diagrams.



**Figure 5. Comparison between crash and sledtest for the right leg.**



**Figure 6. Comparison between crash and sledtest for the left leg.**

Due to the fact that the intrusion system has only one platform for moving both feet a priority which feet will be reproduced has to be set. In the shown test the optimization was made for the right leg. In this case the

loads between sled and crashtest are very close, which is verified in Fig.5. In comparison to that the loads on the left leg shows more differences (Fig.6).

### SUMMARY AND CONCLUSION

PARS owns with the intrusion system a test tool which is utilized in static laboratory tests as well as in sledtests. The intrusion system is in use for several studies to develop protective devices for lower extremities. These are for example foam, airbag, optimized foot controls and other constructive solutions.

At this time PARS works out a second state of development of the foot well intrusion system. This system will be fitted out with two foot panels to reproduce the different loads and movements of each foot. Further development goals are the reduction of the accelerated mass as well as modifications on the mechanical parts.

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# PREDICTING PROXIMITY OF DRIVER HEAD AND THORAX TO THE STEERING WHEEL

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## ABSTRACT

The distance between the driver and the steering-wheel airbag module at the time of deployment has been identified as an important factor affecting the frequency and severity of airbag-induced injuries. Pre-crash positioning may influence the clearance at the time of deployment. Data from in-vehicle studies of driving posture were analyzed to determine the clearance between the steering wheel and the driver's head and chest in normal driving postures. Driving postures of over four-hundred men and women were recorded in twenty-two different vehicle conditions representing a wide range of seat heights, steering-wheel-to-pedal distances, and seat cushion angles. The data were used to generate predictive statistical models of the distribution of clearances between the driver's torso and the steering wheel. The findings have implications for vehicle design and airbag-injury countermeasures.

## INTRODUCTION

Many airbag-related injuries, including abrasions, fractures, and atlanto-occipital separations occur when the driver interacts with the airbag before it is fully deployed. This occurs when the occupant is out of position, or too close to the airbag module as a result of being unbelted and/or sitting close to the steering wheel when driving. Several studies have indicated that smaller distances between the occupant and airbag at the time of deployment are associated with higher frequency and severity of airbag-induced injuries, and higher loading in human surrogates (1-7).\*

Parkin et al. (8) investigated the distances between driver heads and the steering wheel by filming a thousand drivers as they passed a fixed camera. Among other conclusions, female drivers were found to sit closer to the steering wheel than male drivers, and elderly drivers were observed to sit further forward than their younger counterparts. It was also estimated that 25% of the observed population were positioned so that the nasion landmark was within 45.4 cm of the steering wheel center. The occupants' gender and age were deduced from the photos, but no actual anthropometric data were available to distinguish between the effects of stature, gender, and

age. Also, no vehicle package dimensions were included in the analysis.

De Leonardis et al. (9) measured driver position, defined by nasion and xiphoid landmarks, relative to the steering wheel for over 600 drivers and found that 5% of the female population sit closer than 254 mm (10 in) to the steering wheel. Most of the data were collected under static (non-driving) conditions in the subjects' vehicles, and no attempts were made to relate vehicle interior geometry to the response variables, although the paper did suggest a relationship between vehicle wheelbase and driver proximity to the steering wheel. The authors also concluded, through data collected on thirteen short-stature subjects, that many drivers sitting closer than 254 mm could adjust their seats to increase the distance to the steering wheel to over 254 mm of clearance in selected vehicles.

A series of studies at the University of Michigan Transportation Research Institute (UMTRI) have investigated driver posture and position in vehicles (10-12). Although the primary goal of these studies was to determine driver preferred seat position, seatback angle, and eye location, data on driver proximity to the steering wheel were also obtained. These data include the distance from the steering wheel center to the driver's chin and manubrium (top of sternum), and the minimum horizontal distance between the driver and the steering wheel center when seated in a normal driving posture. These data provide information about preferred position of drivers spanning a wide range of stature under normal driving conditions. These distances represent maximum clearances at the time of airbag deployment, since, in a frontal impact, the distance to the steering wheel will decrease during vehicle deceleration.

The driver-to-steering-wheel proximity data from these studies were used along with subject anthropometry and vehicle package measurements to develop predictive equations that describe the distribution of proximities to the steering wheel based on the male and female stature distributions of the driver population, steering-wheel-to-BOF (ball of foot) distance, and seat-cushion angle of the vehicle. This paper describes the analysis procedures and provides the preliminary prediction equations.

\* Numbers in parentheses designate references provided at the end of this paper.

## METHODS

### Subjects\*

Anthropometric measures that were considered possible predictors of driver proximity to the steering wheel include: stature, gender, age, weight, and body proportion (ratio of torso length to leg length). Test subjects were selected to span a range of these parameters in order to determine the effect of these factors on proximity to the steering wheel. A stratified sampling strategy was considered optimal where the short and tall drivers are oversampled to assure adequate data at the extremes of the population. The data are later weighted to represent a defined population stature distribution (e.g., U.S. or Japanese population) or to represent different gender mixes of a defined target population.

In each study, subjects were selected to fill twelve gender/stature groups, as described in Table 1. The groups include subjects who are shorter than the 5th-percentile female stature and those who are taller than the 95th-percentile male stature, based on the 1974 U.S. HANES survey (13). An effort was made to sample subjects over a wide range of weight, body proportion, and age, in order to span most of the anthropometric variance present in the population. The subjects were recruited from the southeast Michigan area through newspaper advertisements. All subjects were required to have at least four years of driving experience and a valid driver's license. Data were available for over four-hundred drivers, equally divided among the stature/gender classifications with 60-120 subjects in each study.

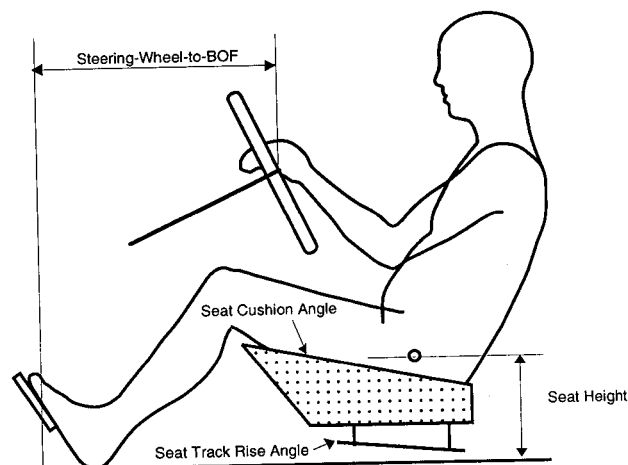
**Table 1.**  
**Summary of Subject Sampling Plan**

Group	Gender	Percentile Stature Range	Stature Range (mm)
0	Female	< 5th	under 1511
1	Female	5-15	1511 - 1549
2	Female	15-40	1549 - 1595
3	Female	40-60	1595 - 1638
4	Female	60-85	1638 - 1681
5	Female	85-95	1681 - 1722
6	Male	5-15	1636 - 1679
7	Male	15-40	1679 - 1727
8	Male	40-60	1727 - 1775
9	Male	60-85	1775 - 1826
10	Male	85-95	1826 - 1869
11	Male	> 95th	over 1869

\* The rights, welfare, and informed consent of the volunteer subjects who participated in this study were observed under guidelines established by the U.S. Department of Health and Human Services on Protection of Human Subjects and accomplished under medical research design protocol standards approved by the Committee to Review Grants for Clinical Research and Investigation Involving Human Begins, Medical School, The University of Michigan.

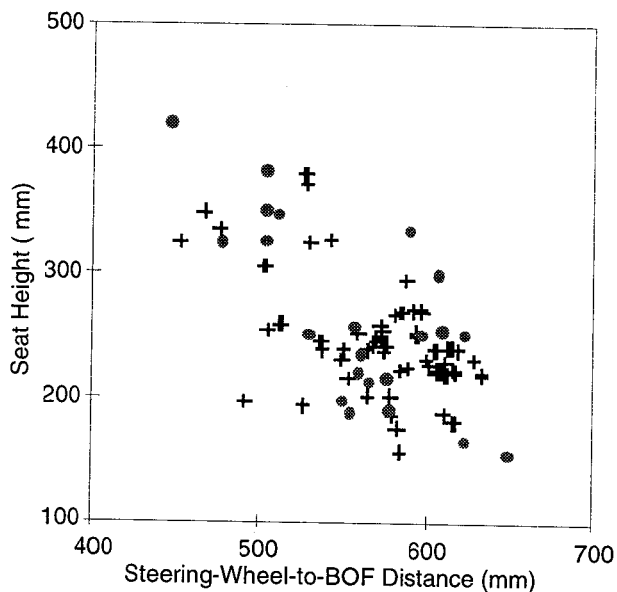
### Test Conditions

Data were collected in twenty-two vehicles that were carefully chosen to span ranges for several variables that have been identified as the primary factors influencing driver selected seat position and driver eye position. These include seat height (H30), horizontal steering-wheel-to-BOF distance (the horizontal distance between the center of the steering-wheel-rim plane and the BOF landmark defined in SAE J1516), transmission type (manual or automatic), seat-track rise angle and seat-cushion angle (10-12). Figure 1 illustrates some of these package factors.



**Figure 1.** Illustration of relevant vehicle package factors.

Figure 2 shows a scatter plot of seat height versus steering-wheel-to-BOF distance for late-model vehicles. There is a clear trend for decreasing wheel-to-pedal distance with increasing seat height that is necessary for accommodating drivers of a range of body size at all seat heights. The solid circles show the vehicle conditions tested that were specifically chosen to span a wide range of the levels of these variables in the vehicle fleet. Seat-cushion angle is a relatively new measure added to SAE J826 in 1996 that quantifies the angle of the loaded seat cushion under the driver's buttock and thighs (14).



**Figure 2. Seat height vs. steering-wheel-to-BOF distance for late-model vehicles. Circles indicate test conditions.**

Table 2 summarizes the important package dimensions present in each test vehicle. All dimensions were measured directly from the test vehicles. Many vehicles were modified from the original design specifications for the purposes of the study and do not represent actual production vehicles.

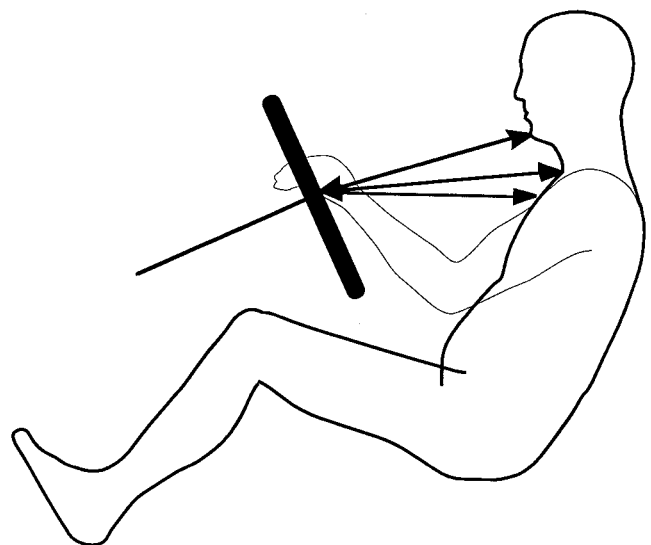
**Table 2**  
**Summary of Relevant Vehicle Characteristics\***

Vehicle	Seat Height (mm)	Seat Cushion Angle (deg)	Wheel-to-BOF Distance(mm)
A	154	15.5	650
B	165	14.0	623
C	189	16.6	577
D	188	19.0	555
E	197	11.3	550
F	212	22.5	565
G	216	17.0	576
H	220	17.7	559
I	234	18.0	561
J	250	17.7	597
K	250	16.0	530
L	250	12.0	623
M	254	13.0	610
N	257	12.0	557
O	298	11.3	607
P	326	14.0	504
Q	333	12.5	589
R	346	13.0	512
S	349	13.0	504
T	381	10.0	504
U	324	13.0	478
V	420	9.5	447

## Data Collection Procedure

Data collection procedures have previously been described (10-12). The same general procedures were used for all vehicle testing. The subject completed a consent form, health questionnaire, and a survey asking about their current vehicle and driving habits. A set of twenty standard anthropometric measures were taken, including stature, weight, and sitting height. The subject was tested in each of several vehicles in a predetermined random sequence. The initial position of the seat, seatback, and steering wheel in each trial were the same for every subject and were set to mid-range, rather than extreme positions, as the latter has been found to bias the results. The subjects were instructed on the operation of the seat and steering wheel adjustments and were asked to experiment extensively with the adjustments to find a comfortable driving posture and position.

The subject was encouraged to continue to adjust his or her posture while driving over a 15- to 20-minute road route. The subject was asked to find the most comfortable driving position and to notice the posture of their head in straightahead driving. Immediately after the drive, the subject's location and posture were measured while the subject maintained a relaxed, normal driving position. In addition to other posture and position data, three measures related to proximity to the steering wheel were collected: chin-to-steering-wheel-center distance, manubrium-to-steering-wheel-center distance, and the minimum horizontal distance between the driver and the steering wheel center, as illustrated in Figure 3. All measures were made to the centerline of the driver's body, compressing clothing when necessary, with the driver in a normal driving position.

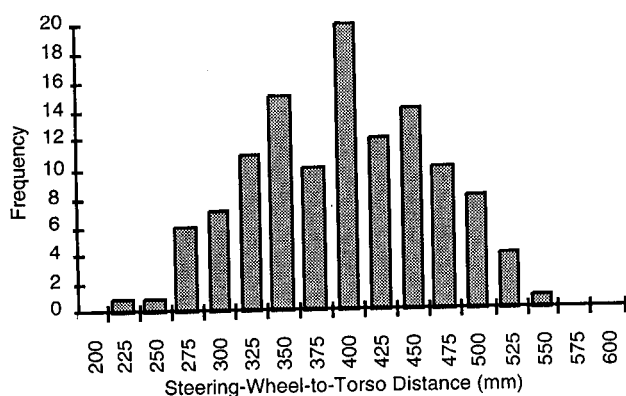


**Figure 3. Measures of driver proximity to steering wheel.**

The driver proximity measurements were compiled and weighted to represent the U.S. population with a 50:50 gender mix based on the stature distributions in HANES survey data (13). All distances measured were to the center of the plane of the steering wheel rim. Although many steering wheel centers are either dished into or protrude past this rim plane, previous UMTRI studies (10-12) suggest that the tasks of grasping and operating the steering wheel strongly influence driver posture and therefore the relationship between driver torsos and the center of the steering wheel rim will have a relationship that is most amenable to prediction. The distance between the actual center of the wheel hub and the center of the steering wheel rim face can be added or subtracted later to more accurately reflect clearance in a specific vehicle.

## RESULTS

Figure 4 shows a histogram of the raw data for driver minimum clearance for one vehicle (N = 120). Table 3 reports the percentage of the U.S. population sitting less than the 200-mm, 250-mm and 300-mm clearance levels for the dynamically tested vehicles. These percentages were calculated by weighting the data according to the percentage of the population represented by each subject.



**Figure 4. Histogram of minimum clearance to the center of the steering wheel for a typical vehicle.**

Because of the variance in the data and past success modeling driving posture and position (10-12), the analysis effort focused on the development of a predictive model. Statistical modeling provides insight into the anthropometric factors that influence driver position and allows differentiation between the effect of stature, gender, and age. Although information on the distribution of proximities could be obtained through subject testing with each new vehicle design, a good predictive model provides this information with less time and cost. Most importantly, a model can provide insight into the vehicle factors and mechanisms that influence driver position, which can be used to design vehicles to better

accommodate the driving population, while potentially increasing the distance between short drivers and the steering wheel airbag module.

**Table 3  
Data Summary**

Vehicle	Percent of Population Closer than		
	200 mm	250 mm	300 mm
A	0.00	3.25	25.75
B	3.83	7.12	22.08
C	0.00	0.50	6.50
D	1.39	3.89	10.03
E	0.00	0.00	0.00
F	0.00	0.00	10.00
G	0.50	7.00	18.50
H	0.25	2.50	13.75
I	2.14	4.39	14.41
J	0.25	1.00	9.75
K	3.28	4.79	5.62
L	4.39	7.03	23.22
M	5.50	16.00	34.50
N	0.00	7.25	25.50
O	0.00	0.25	8.67
P	0.00	0.28	3.86
Q	4.00	8.00	22.00
R	0.00	1.50	11.75
S	0.00	3.00	12.00
T	1.39	4.39	13.91
U	1.50	5.79	8.12
V	0.00	0.00	3.75

## Model Development

**Choice of Dependent Measure** - As expected, correlations between the three steering-wheel clearance measures are very high. The correlation between steering-wheel-to-chin and steering-wheel-to-manubrium distances is the highest, at  $r=0.96$ . The correlations of the minimum horizontal distance between the driver and the steering wheel center with steering-wheel-to-chin and steering-wheel-to-manubrium distance are 0.80 and 0.87, respectively.

The high correlations indicate that predictive models of the three variables will be very similar and that any one measure would be sufficient to identify the effects of vehicle and subject variables on driver-to-steering-wheel proximity. The minimum horizontal distance between the driver and the steering wheel center was selected primarily because it represents a minimum distance, or worst-case measure.

**Wheel-Proximity Database** - There are 22 production vehicles in the UMTRI wheel-proximity database. Subjects were tested in each vehicle under dynamic conditions. The statistical approach taken is described in detail in Flannagan et al. (11). During the modeling process, inspection of the data indicated that data from

three of the vehicles were outliers, in that they produced steering-wheel-to-driver distances that are greater than expected based on the pattern of results from the other nineteen vehicles. Because these vehicles would cause the model to overestimate distance to the wheel for the majority of vehicles, they were deleted from the modeling process until further understanding of the source of the difference is obtained. Thus, across all vehicles, the model can be considered slightly conservative. On average, however, the model is expected to produce results appropriate to most production vehicles

**Checking Basic Assumptions** - The first step in developing the model was to check basic assumptions required for the modeling approach to be used. First, population stature is assumed to be normally distributed within gender, based on data from Abraham et al. (13). Second, stature and wheel proximity must be linearly related throughout the range of stature. Data from each vehicle were individually graphed and inspected, and in every case, the relationship was linear throughout the range. Interestingly, even in vehicles with censoring in seat position (i.e., the seat track did not have enough travel fore or aft for some subjects), there was no apparent censoring of minimum horizontal distance between the driver and the steering wheel center. Drivers apparently use seatback angle and other postural changes in the upper body to compensate for restrictions in seat positions (i.e., hip locations).

The third assumption is that the distribution of unexplained error is the same across all values of the independent variable, stature. This assumption was checked by regressing wheel proximity on stature separately for each vehicle, and inspecting the residuals for signs of heteroscedasticity (i.e., unequal variance across stature). In particular, it was hypothesized that people at the extremes of the stature distribution might show less variability in measures of proximity to the steering wheel than people in the middle of the distribution. However, no vehicles showed clear evidence of decreased variance at either tail. Data from the laboratory buck study, in which subjects had ample seat-track travel, showed minimal heteroscedasticity. These analyses demonstrate that the equal-variance assumption is reasonable.

In addition to these basic assumptions, the data support additional simplifying assumptions that make both the modeling process and the end result more straightforward. First, stature does not interact with vehicle variables, such as seat height or steering wheel position, in its effects on wheel proximity. Second, vehicle variables do not affect the variability of wheel proximity. Third, the effect of stature on wheel proximity is the same for males and females. Although age was also shown to influence wheel proximity, the effect of age is so small relative to the effect of stature that the increased complexity of the model was not considered worth the small improvement in predictive power.

These three important results make it possible to separate modeling of the effects of vehicle variables from the effects of stature. Specifically, vehicle variables need only be considered in predicting mean wheel proximity. In addition, the same set of equations can be used to predict parameters of the wheel proximity distribution for both males and females.

**Modeling the Effects of Vehicle Variables** - Because the sample of drivers in each vehicle was stratified by stature, it is necessary to weight each observation according to its likelihood of occurrence in the population. Once weighted, median observed wheel proximities were calculated for each vehicle. In a normal distribution, the mean and median are the same. Although a weighted mean could have been used as the empirical measure of central tendency, the median was chosen, since it should be influenced less by unusual characteristics of the distributions.

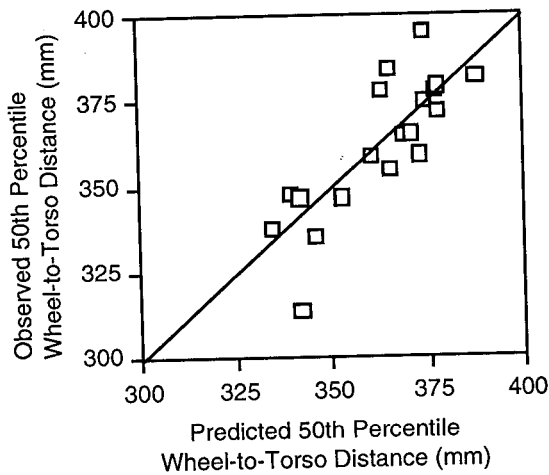
Using nineteen vehicles from the database, median wheel proximity (for a 50%-male U.S. stature population) was regressed on seat height, seat-cushion angle, wheel-to-BOF distance, transmission type, and predicted seat position, using the Seating Accommodation Model (11). The resulting equation ( $R^2 = 0.72$ ) is:

$$\hat{\mu} = 464.7 - 0.278w + 3.55p \quad (1.)$$

where,

$\hat{\mu}$  = predicted mean of driver proximity to wheel distribution,  
 $w$  = wheel-to-BOF distance (mm), and  
 $p$  = seat-cushion angle (degrees).

Figure 5 shows the observed-versus-predicted median wheel proximities for the vehicles used in dynamic testing. The regression equation predicts median wheel proximity well, at least for a 1:1 male-female U.S. population distribution. It is important to note that, although Equation 1 was generated from medians of the male-female combined distribution, it can be used to predict means for male-only and female-only wheel-proximity distributions because the effects of vehicle variables and stature on wheel proximity are the same for males and females.



**Figure 5. Observed versus predicted 50th-percentile wheel proximity for nineteen vehicles.**

**Modeling the Effects of Stature** - The next step was to determine the relationship between wheel proximity and stature, and to incorporate stature effects into the model. For each vehicle, wheel proximity was regressed on stature, and the slope, intercept,  $R^2$ , and mean squared error of the linear fit were recorded. The mean squared error is the estimate of the unexplained variance in the data.

The mean of the stature coefficients of the twenty-one vehicles, weighted by the number of subjects in each vehicle after excluding censored observations, is 0.437. This becomes the model coefficient for mean stature. To incorporate the stature component into Equation 1, the intercept was recalculated so that predictions of mean wheel proximity remain the same for 1:1 male-female U.S. stature distribution. The new prediction equation for mean wheel proximity becomes:

$$\hat{\mu} = -271.2 + 0.437\mu_s - 0.278w + 3.55p \quad (2.)$$

where,

$\mu_s$  = mean stature of single-gender (male or female) driver population,

$\hat{\mu}$  = predicted mean wheel proximity (mm aft of steering wheel center),

$w$  = wheel-to-BOF distance (mm), and

$p$  = seat-cushion angle (degrees).

The weighted mean of the mean squared error is 29.75. Using the values for the slope and mean squared error, the prediction equation for the standard deviation of the wheel-proximity distribution becomes:

$$\begin{aligned} \hat{\sigma} &= \sqrt{(.437)^2 \sigma_s^2 + (46.87)^2} \\ &= \sqrt{.191\sigma_s^2 + 2197} \end{aligned} \quad (3.)$$

where,

$\sigma_s$  = standard deviation of stature distribution of male or female driver population

$\hat{\sigma}$  = predicted standard deviation of single-gender wheel-proximity distribution

#### **Combining Male and Female Predicted Wheel Proximity**

Equations 2 and 3 define the wheel-proximity model. However, these equations are designed to be used on male and female driver population distributions separately. For most vehicles, the target population will be some mixture of males and females, so the two predicted wheel-proximity distributions need to be combined to estimate population percentiles of wheel proximity.

In most cases, using the two distributions to generate percentiles is simple. For the median wheel proximity, the two predicted means can simply be averaged in proportion to the gender mix. That is:

$$\hat{\mu} = k\hat{\mu}_M + (1-k)\hat{\mu}_F \quad (4.)$$

where,

$\hat{\mu}$  = predicted mean of mixed-gender wheel-proximity distribution,

$k$  = proportion of males in the target population,

$\hat{\mu}_M$  = predicted mean of male wheel-proximity distribution, and

$\hat{\mu}_F$  = predicted mean of female wheel-proximity distribution.

For population wheel-proximity percentiles at or below the 5th, or at or above the 95th, the overlap between the single-gender distributions is so small that the appropriate tail percentile of either the male or female distribution alone is sufficiently accurate. For example, the 10th percentile of the female wheel-proximity distribution is a reasonable approximation of the 5th percentile of a 1:1 mixture of males and females. The general formula is given in Equations 5 and 6.

To find the appropriate percentile at the lower tail, use:

$$p_f = \frac{p_t}{1-k} \quad (5.)$$

where,

$p_t$  = target population percentile,

$k$  = proportion of males in the target population, and

$p_f$  = percentile of the female-only distribution that corresponds to the target percentile of the combined distribution.

At the upper tail, use:

$$p_m = 1 - \frac{1-p_t}{k} \quad (6.)$$

where,

$p_t$  = target population percentile,

$k$  = proportion of males in the target population, and

$p_m$  = percentile of the male-only distribution that corresponds to the target percentile of the combined distribution.

For cases in which target wheel-proximity percentiles are between 5% and 95% but not 50%, or the male-female ratio is very different from 1:1, the normal mixture function must be solved for the desired value. The function is given in Equation 7 and can be solved for  $x$  using various numerical methods.

$$p = k\Phi_M(x) + (1-k)\Phi_F(x) \quad (7.)$$

where,

$\Phi(x)$  = the cumulative normal distribution for random variable  $X$  with mean,  $m$ , and variance,  $s^2$ , and

$p$  = target percentile of the population wheel-proximity distribution.

**Model Summary** - To use the model to determine driver proximities for a particular vehicle and driver population, follow the following steps:

1) Determine the values for vehicle measures of wheel-to-BOF distance and seat-cushion angle, the values for mean and standard deviation of male stature, mean and standard deviation of female stature, and the proportion of males in the driver target population.

2) Estimate the mean of the male wheel-proximity distribution by using wheel-to-BOF distance, seat-cushion angle, and the mean of the male stature distribution, and Equation 2:

$$\hat{\mu} = -271.2 + 0.437\mu_s - 0.278w + 3.55p \quad (2.)$$

3) Calculate the standard deviation of the male wheel-proximity distribution using the standard deviation of the male stature distribution and Equation 3:

$$\hat{\sigma} = \sqrt{.191\sigma_s^2 + 2197} \quad (3.)$$

4) Repeat steps 2 and 3 for females.

5) Generate population percentiles of wheel proximity as follows:

1) 50th percentile:

$$\hat{\mu}_s = k\hat{\mu}_M + (1-k)\hat{\mu}_F \quad (4.)$$

2) 5th percentile or less:

$$p_a = \frac{p_t}{1-k} \quad (5.)$$

3) 95th percentile or greater:

$$p_m = 1 - \frac{1-p_t}{k} \quad (6.)$$

4) all other percentiles, solve for  $x$  in:

$$p = k\Phi_M(x) + (1-k)\Phi_F(x) \quad (7.)$$

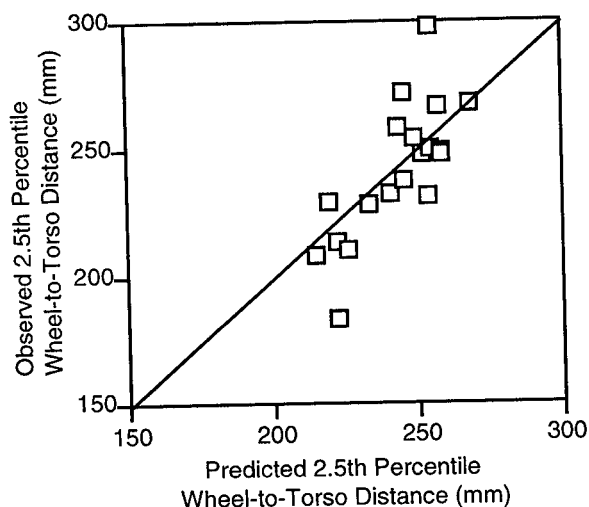
**Model Performance** - To test the performance of the model, observed 2.5th, 5th, and 50th percentiles of the wheel-proximity distribution were calculated for each of twenty-two vehicles. The observed percentiles were calculated using the same approach embodied in the wheel-proximity model. For each vehicle, wheel proximity was regressed on stature, and the slope, intercept, and mean squared error were recorded.

To calculate observed mean wheel proximity for males for a given vehicle, the slope, intercept, and standard error of the relationship between wheel proximity and stature was determined. Using the mean and standard deviation of U.S.-male stature, the mean and standard deviation of the observed wheel proximity distribution were calculated. The process was repeated for the female mean and standard deviation of stature. Once the mean and standard deviation of the wheel-proximity distributions were calculated, percentiles were determined according to Equation 4, 5, 6, or 7, as appropriate.

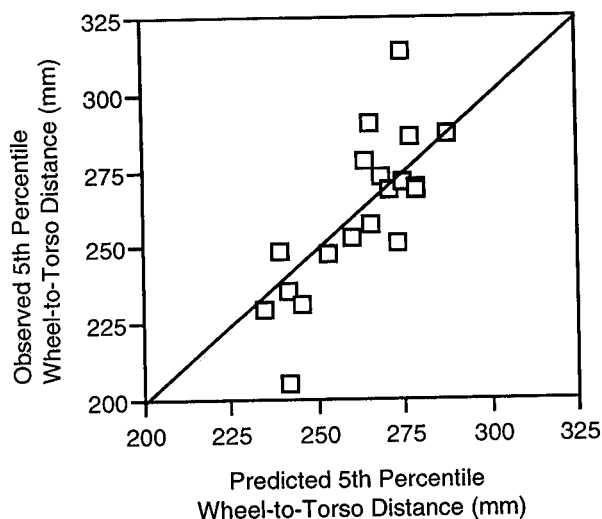
For each vehicle, the wheel-proximity model was used to predict percentiles of the wheel-proximity distribution. Figure 6 shows the model performance at the 2.5th percentile across all target populations for all vehicles. On the whole, the model is reasonably accurate at the 2.5th percentile. There are three residuals greater than 25 mm, but for most vehicles the prediction is good at this outer percentile.

Figures 7 and 5 show model performance at the 5th and 50th percentile, respectively. At the 5th percentile, the average residual is -1.8 mm and the largest residual is 39 mm. At the 50th percentile, the largest residual is 28 mm, and the average residual is -1.3 mm. Model performance is good, particularly in the middle of the distribution. Predictions of tail percentiles are off by

more than 25 mm for a few vehicles, but overall the model seems to accurately predict percentile proximities to the steering wheel.



**Figure 6. Observed versus predicted 2.5th-percentile wheel proximity.**



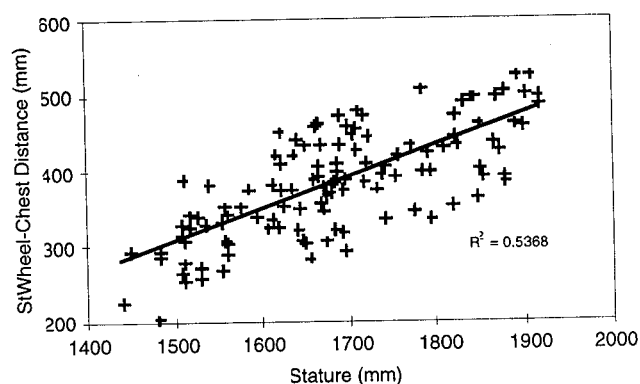
**Figure 7. Observed versus predicted 5th-percentile wheel proximity.**

## DISCUSSION AND CONCLUSIONS

This investigation utilized data on driver proximity to the steering wheel for more than 400 drivers tested in nineteen vehicles to develop a predictive model for driver position relative to the steering wheel. The data show that driver position relative to the steering wheel can be predicted by anthropometric, vehicle, and seat factors. The three primary factors that affect the proximity of the driver to the center of the steering wheel are driver stature, steering-wheel-to-BOF distance, and seat cushion angle. The data suggest a model by which the distribution

of driver proximities to the steering wheel can be predicted for any vehicle if the characteristics of the male and female stature distributions in the target driver population are known.

Driver stature has the most dominate effect on driver proximity to the steering wheel with shorter drivers tending to sit closer to the wheel than taller drivers, as illustrated in Figure 8. The analysis suggests that this effect is independent of driver gender so that male and female drivers of identical height sit, on average, the same distance from the steering wheel. Gender mix of the target population is used in the model only because men and women have distinctly different stature distributions and not because the data support a true gender effect.

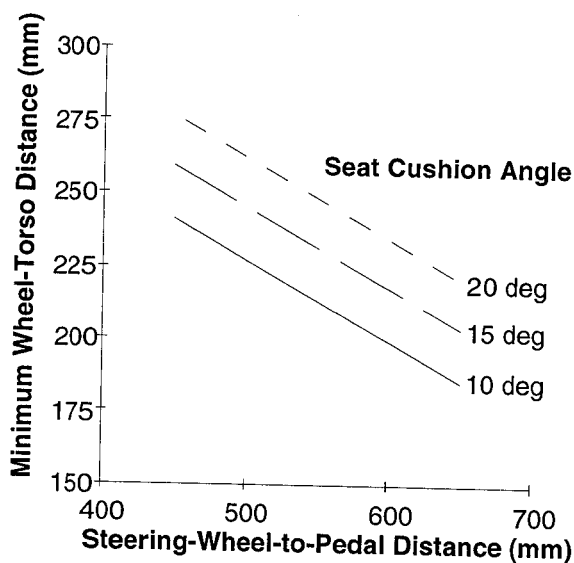


**Figure 8. Illustration of the effect of driver stature on proximity to the steering wheel.**

One package factor, the horizontal distance between the center of the steering wheel rim plane and the BOF landmark on the accelerator pedal, was found to have an effect on driver proximity to the steering wheel. As steering-wheel-to-BOF distance decreases, the distance between the driver and the wheel increases by 28% of the change in the wheel position. Other package factors that were found not to significantly affect proximity include seat height and transmission type. Although driver's selected seat positions are further forward (closer to the pedals) in vehicles equipped with manual transmissions, the effect of this on driver proximity to the steering wheel is canceled out by more reclined seatback angles (10).

One seat factor, seat-cushion angle, affects driver proximity to the steering wheel. As seat-cushion angle increases, driver-selected seatback angle increases, subsequently increasing the torso-wheel distance. A ten-degree increase in seat cushion angle increases the distance between the driver and the steering wheel by approximately 35 mm. Figure 9 shows the effect of steering-wheel-to-BOF distance and seat-cushion angle on driver proximity to the steering wheel.





**Figure 9. Illustration of the effect of wheel position and seat cushion angle on proximity of drivers' torsos to the steering wheel.**

Of the factors found to affect the distance between the driver and the steering wheel, only steering wheel position and seat-cushion angle might be changed in a vehicle to increase the distance for shorter drivers. In the vehicles tested, only a small percentage of the subjects sat closer than 254 mm (10 inches) from the steering wheel. A relatively small increase of 30-40 millimeters in clearance to the wheel would bring most of those above the 254-mm distance suggested to be safe for airbag deployment. The model presented predicts driver position relative to the center of the plane of the steering wheel rim, thus calculations for dishd or protruding airbag modules should be offset accordingly.

#### ACKNOWLEDGMENTS

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# RESTRAINT SYSTEM OPTIMISATION FOR MINIMUM SOCIETAL HARM

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## ABSTRACT

The focus of road safety in the past has been on reducing the road toll. This resulted in the introduction of legislation making the wearing of seat belts compulsory in Victoria in 1970. This was a world leading approach that has been of great benefit to the Australian community. More recently, it is being recognised that serious injury, particularly long term and irrecoverable injury to the head and neck are a major concern and cost for the individual and the community. Detailed crash analysis in Australia has identified the wide range and frequency of crash types and severities that occur on Australian roads. Varying occupant protection needs have also been identified, in terms of age, sex, size and seating position. An optimising technique has been developed and applied to the design of the restraint system of a new model Holden Commodore passenger vehicle. Various seat belt retention and webbing characteristics, airbag and inflator characteristics, seat stiffness and anti-submarining structures have been considered during the optimising process. A Societal Harm measure of the cost of injury was used to evaluate the effectiveness of the restraint system in providing protection to the community in the range of real-world crashes which occur. This technique is proposed as a more appropriate approach to restraint system design than designing for government regulations or consumer information tests.

## INTRODUCTION

Motor vehicle accidents are causing increasing concern in the community, as evidenced by the high profile media coverage given to motor vehicle crashes. Accidents have been identified as a major cause of injury and death, and thus the cause of major social and economic costs to the community.

Head injury is appropriately called the silent epidemic. There has been a dramatic increase in head injury over the last decade, not as a result of increased accidents, but because of increased survival. This has resulted from the use of ambulances with life support systems, helicopter ambulances and the use of CAT scans to identify haemorrhaging and location of blood clots. There is a growing awareness of the incidence of non-fatal head injury and its impact on the individual, the family unit and the

community. Similarly, the long term and debilitating effects of relatively low severity neck injury are not adequately recognised in a strategy to simply reduce road fatalities. Consequently, there is growing concern for developing strategies for reduction of injury frequency and severity.

The objective in vehicle safety development at Holden is to protect car occupants by minimising their injury risk. Media focus is usually on safety devices, such as new seat belts or airbags, or on consumer information test results. This focus does not recognise that the injuries that occur on Australian roads are the result of a spectrum of crash types and severities, of vehicle crash performance and of occupant vulnerabilities. In developing vehicle safety to provide the maximum benefit to the community, a broader consideration of injury risk reduction must be given. The complete vehicle, with its structure, its restraint system and its occupants, must be developed as a total system. The front structure must be designed to absorb crash energy efficiently at the lowest loads possible. The passenger compartment must support the crash loads generated. On this foundation, the restraint system can be optimised for the broadest spectrum of passenger protection.

## Protection Requirements

The crash parameters which determine the injury risk to vehicle occupants are the severity of the crash, the behaviour of the vehicle structure and restraint system, and the vulnerability of the passengers. The crash severity is basically determined by the collision speed, and the stiffness and mass of the car or obstacle struck. The behaviour of the vehicle system is determined by the way energy is absorbed, by the strength of the passenger compartment, and the characteristics of the restraint system. The vulnerability of car occupants is determined by their seating position, health, size, sex and age.

Legislative regulations in all industrialized countries set requirements for the performance of vehicles in crash tests. Consumer information organisations conduct tests at higher speeds with the objective of evaluating relative safety performance, on the assumption that measurements made during a higher speed barrier test would indicate improved field performance. Vehicle design must satisfy the government regulation for performance at 48 km/h frontal collision with 50th percentile male dummies in the mid-seating position.

It must also provide protection for all vehicle occupants, many of whom are small females, or large males, or older people with more fragile bones, and who will become involved in a range of collisions at various speeds, at various angles and overlaps, and with obstacles and other vehicles of various sizes and stiffness. Vehicle system performance must result in minimum injury risk to all vehicle occupants in all accident situations.

Developing a restraint system with the single focus of minimizing injury risk in a single laboratory test, as measured by the response of the test dummy representing the mid-sized male in the mid-seating position, does not recognise the additional, and possibly conflicting protection needs of females, the young and the elderly, nor the risks associated with the full spectrum of real world crash types and severities. Current occupant protection technology cannot provide a single design solution that gives optimum protection for every size and fragility of passenger, in each seating position, and for all of the types and severities of crashes that occur in the community.

### **Crash Pulse Optimisation**

Passenger car structures are being developed which will substantially improve the safety of car occupants. The behaviour of the vehicle structure during a collision, so-called vehicle crashworthiness, has the major influence on the occupant injury risk. During a collision, the part of the structure which is deforming due to contact with the impacting object collapses, decelerating the remaining, still undeformed part of the vehicle, including the passenger cell. The deceleration-time signature of the passenger compartment is referred to as the crash pulse. It is ultimately the shape of this crash pulse which determines the severity of the injury risk, as it determines the loading applied to the restraint system.

The severity of a crash is determined by the direction of impact, the collision speed and the shape, stiffness and mass of the car or object struck. Most collisions occur at low speed. The crash pulse must be optimised to balance three conflicting requirements:

1. Minimum vehicle damage in low speed crashes.
2. Minimum deceleration and hence occupant loading for the most frequent injury causing crashes.
3. High energy capacity for high speed collisions.

### **Accident Investigation**

Road accident research is conducted in order to obtain an understanding of the accident injury risks in the Australian environment. This research is contracted to

Monash University's Accident Research Centre (MUARC). The MUARC team investigates the majority of crashes in Australia involving a Commodore airbag deployment, plus a large number of non-airbag Commodore collisions, both front and side impact crashes. The data they collect is progressively analysed to measure the effectiveness of changes made to the Commodore safety system. These analyses involve measuring the injury risk for each injury level and the evaluation of the statistical significance of the differences between data. As a result of this research, an understanding of the risks and the value of safety improvements in the Australian environment is being developed.

### **Societal Harm**

Societal Harm is a metric for quantifying injury costs from road trauma, involving both a frequency and a unit cost component [2]. In its most general form, it is a measure of the total cost to the community of road trauma, and includes hospital costs, rehabilitation costs, lost income and some value on lost ability and quality of life. It can also be used to evaluate the contribution made by vehicle design for occupant protection.

The concept of Societal Harm was introduced in the 1980's in the USA to evaluate the benefits of road safety countermeasures [8]. It provides a broader vehicle design perspective than design for fatality reduction alone. This type of analysis helps focus attention on the relative importance of injury as a leading health risk in the community, and allows a systematic priority setting for safety development. It allows the development of more sophisticated restraint systems including airbag systems.

The Societal Harm technique is similar to the WIC technique introduced by Viano and Arepally [14], but is based on a cost factored analysis. Based on the costing of motor vehicle injuries done by Miller, for the US Federal Highway Administration [10], the initial steps to a biomechanical injury cost model were taken by Newman [11] using a model with dummy-based injury assessment functions, to predict the probability of occurrence and the probable cost of specific AIS injuries, despite the model being tentative in some areas of the Injury Assessment Functions used.

The Abbreviated Injury Scale (AIS) does not measure impairment or disability. An injury of the same AIS to different body regions can have a significantly different rate of recovery, and functional loss can occur in one region but not in another. In addition, females, children and older people have different fragilities to young males, and an injury with the same AIS rating may

have a significantly different effect on each of these groups.

A national data based is used to evaluate the potential benefits of any proposed vehicle design change. The database contains information from the Federal Office of Road Safety's National Fatality File, the hospitalised sample of crashes from the MUARC Crashed Vehicle File and medically treated cases from the Transport Accident Commission in Victoria. Injury severity was evaluated using the Association for the Advancement of Automotive Medicine's Abbreviated Injury Scale (AIS 85). Using this information, a Cost of Societal Harm in Australia Matrix by AIS and body region has been developed by MUARC, for use in this restraint optimisation process.

## RESTRAINT SYSTEM OPTIMISATION

An optimising technique based on a Multiple Step Taguchi Method was used to drive a MADYMO evaluation of restraint system parameters to arrive at a design providing a Minimum Societal Harm solution. It incorporates a numerical optimisation procedure utilising an orthogonal grid method [13], a form of direct search method modified to increase the rate of convergence. Objective function values are used for constructing the solution algorithm. The objective function to be optimised is defined as:

$$G = \sum_{i=1}^3 W_i f_i$$

where -

$G$  is the objective function, Societal Harm,  
 $f_i$  is the  $i$ -th sub-objective function ( $i=1,3$ ), and  $W_i$  is the weighting factor for  $f_i$  ( $i=1-3$ )

The  $f_i$  represents the percentage of the  $i$ -th injury with respect to its limit, and  $W_i$  is the statistically significant factor of the  $i$ -th injury type which ranks the priority of the  $i$ -th injury type.

Based on the results of a sensitivity analysis, parameters from the restraint system were selected as design variables, denoted by  $X_j$  ( $j=1,8$ ). The upper and lower boundaries for the  $j$ -th variable are defined as  $X_{\max,j}$  and  $X_{\min,j}$ , and the mathematical model for the optimisation process is expressed as -

$$\text{Min. } G = \sum_{i=1}^3 f_i W_i$$

with constraints  $X_{\min,j} \leq X_j \leq X_{\max,j}$  ( $j=1,\dots,8$ )

The optimisation procedure is illustrated in Figure 1. MADYMO software was used as a solver to calculate the injury values for various design configurations. The modified orthogonal grid method was implemented as an optimising module of the program. The data exchange between the optimiser, and MADYMO input and output is conducted by the main controller in the program.

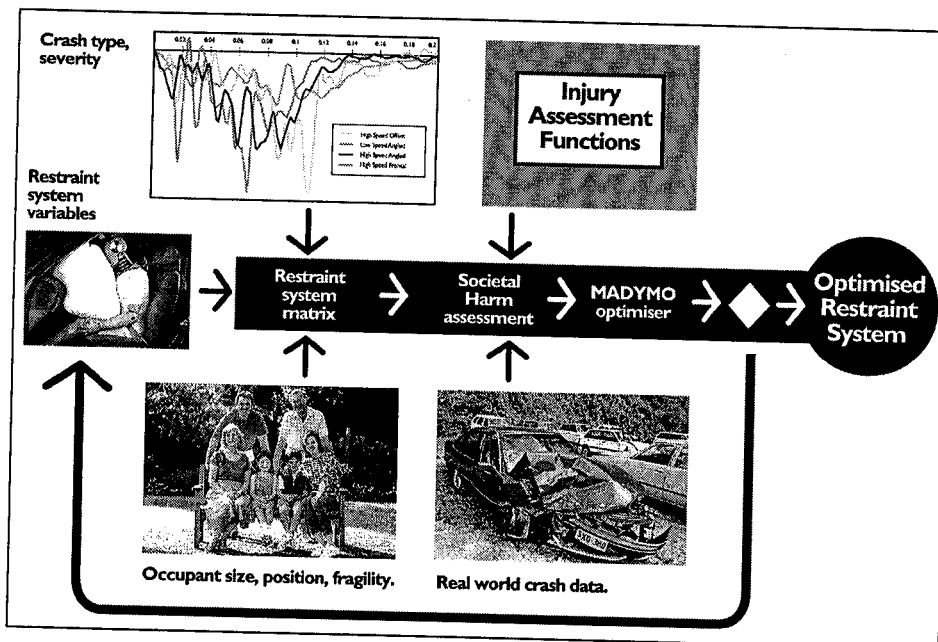


Figure 1. Schematic Illustration of Restraint System Optimisation Process

## FUTURE APPLICATIONS

An important future application of this technique will be in the development of side impact protection. There are specific injury risks associated with side impact crashes. The strategies currently being used to achieve the performance levels required by government regulation and consumer information body testing will not achieve appropriate occupant protection. There is a risk that these measures may even be counter productive, by encouraging vehicle design to achieve the desired dummy response which increases the risk to vehicle occupants. This technique of optimising for minimum Societal Harm could be applied to side impact design, in order to optimise occupant protection. A biomechanical injury cost model would ensure that the design characteristics chosen result in benefit to the community, in terms of reduced risk of fatality, brain injury and other societal harm

Before this technique can be applied to side impact protection optimisation, further research and development is required in a number of areas, including the development of validated mathematical models of BioSID and SID IIs test dummies, and improved Injury Assessment Functions to assess the risk of injury from lateral impacts, particularly for brain, neck and lower limb injury. A research project funded by the Australian government and supported by MUARC, GM Holden and others is currently working at addressing this need.

## CONCLUSIONS

An optimising technique has been developed and applied to the design of the restraint system of a new model Holden Commodore passenger vehicle. Seat belt retention and webbing characteristics, airbag and inflator characteristics, seat stiffness and anti-submarining structures have been considered in an optimising process to select the restraint system characteristics which provide the best community protection in the range of real-world crashes in which they will be involved. A Societal Harm measure of the cost of injury was used to evaluate the effectiveness of the restraint system. This technique is proposed as a more appropriate approach to restraint system design than designing for government regulations or consumer information tests.

An important future application of this technique will be in side impact protection optimisation, however further work is required in a number of areas to obtain the information required to support the development of a suitable technique.

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# FRONTAL IMPACTS WITH SMALL PARTIAL OVERLAP: REAL LIFE DATA FROM CRASH RECORDERS

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## ABSTRACT

Impacts with small overlap, or narrow offset impacts, are here defined as impacts with an overlap of less than 30%, often resulting in glance-off. Severe narrow offset collisions are characterised by high closing velocity, fairly low change of velocity, but major intrusion and high intrusion velocity, often resulting in severe injuries. For most car models the main part of the energy absorbing frontal structure is not engaged in this type of impact. Crash tests do not address the performance of the vehicle construction in this type of impact.

This paper presents results from real life collisions, collected in a unique data collection system, where the crash pulse has been recorded in the impact phase. Since 1992, approximately 100,000 crash recorders have been installed, and about 300 crash pulses have been recorded. A crash test with two vehicles of different design regarding the performance in narrow offset impacts is also presented. The study shows that the percentage of moderately and severely injured drivers was higher in impacts with an overlap below 30% than in impacts with an overlap more than 30%. It is also shown that the frontal structure is important for the performance in narrow offset impacts. Reconstructions of these collisions are also discussed.

## BACKGROUND

Real life data shows that approximately 60% of all impacts are frontal impacts (Otte, 1990; O'Neill et al., 1994). Twentyone per cent of all frontal collisions have an overlap below 33% according to O'Neill (1994).

During recent years an increasing attention has been paid on how vehicles perform in impacts with partial overlap. New test methods are developed to better simulate real life impacts with partial overlap, generally 40% or 50%. These crash tests do not, however, address impacts with an overlap below 30 %, in which the main energy absorbing structure of most car models is not engaged. This type of impact, if severe, is characterised

by a high closing velocity but with a relatively low change of velocity and high intrusion velocity. Most often this impact mode results in glance-off.

Narrow offset collisions usually generates a high risk of lower limb injuries, and the risk increases with increased intrusion (Thomas P, 1995). There is also a significant risk for severe skull/brain injuries (Thomas, 1994). The intrusion may be significant not only in the footwell area, but also for the instrument panel. Thomas (1994) shows that 38% of the severe injuries, MAIS 3+, are skull/brain and facial injuries in impacts with an overlap less than 30% and with a  $\Delta V$  exceeding 60 km/h. Thomas (1994) also shows that in high speed impacts,  $\Delta V$  over 60 km/h, with low overlap, the number of severely injured are higher compared to impacts with high overlap and with the same change of velocity. The change of velocity were in that study calculated on the basis of the crush energy.

A study by O'Neill (1994) showed that 12% of all frontal impacts with moderate or severe injuries were impacts with an overlap less than 33%. The study also showed that frontal collisions with an overlap less than 33%, produce moderate or severe injuries in 60 % and fatalities in 10% of those impacts. It is also shown that 14% of all fatal frontal two-car collisions had an overlap below 33% (O'Neill, 1994).

Change of velocity,  $\Delta V$ , or Energy Equivalent Speed, EES (Zeidler et al. 1985), is often used to describe impact severity. In frontal impacts without significant intrusion, change of velocity, mean and peak acceleration has a correlation to injury risk (Kullgren, 1996; Kullgren, 1998). In frontal impacts with an overlap below 30%, and where the intrusions often are significant, intrusion velocity or closing velocity will probably be better correlated to injury risk.

Reconstructions of these impacts with computer simulations, like CRASH3 ("CRASH3 Technical Manual", NHTSA, 1986), are often difficult to assess since the algorithms only work properly when the vehicles in two-car collisions have a common velocity after the impact. In single accidents it is problematic if the vehicle not is hitting a fix object and if it has a

remaining velocity. These types of impacts are not applicable for this type of reconstruction. It is also often difficult to estimate the collision impact site and the collision sequence, since there often is a glance-off after the impact phase, where the vehicles may be far away from each other after the impact. Estimations of closing velocities, or intrusion velocities if possible, are important for better reconstructions of these impacts and to better correlate impact severity to injury risk.

The aim of this study were to present the distribution of accidents and injured in narrow offset impacts and to analyse injury risk based on results from real life impacts, where the crash pulse has been recorded in the impact phase. The aim was also to analyse the performance of different vehicle constructions in narrow offset impacts, based on real life impacts and a crash test. Another aim was to discuss reconstructions of narrow offset impacts and to propose a new reconstruction method for this type of impact.

## MATERIAL/METHODS

The impact severity was measured with a crash recorder. The crash recorder, called Crash Pulse Recorder (CPR), measures the acceleration time history in one direction. The crash pulses have been filtered with approximately 100 Hz. Change of velocity and mean and peak accelerations have been calculated from the crash pulses. The CPR and the analysis of the recordings from the CPR are further described by Aldman et al (1991) and Kullgren et al. (1995).

Since 1992, the CPR have been installed in approximately 100,000, comprising 4 different car makes and 15 models. The car fleet has been monitored for 5 years and every accident with a repair cost exceeding 7000 USD has been reported via a damage warranty insurance. The accident data collection system has been described by Kamrén et al., (1991). At the time this paper was written, approximately 400 accidents have been reported. Included in this study were injury data from 245 frontal collisions and crash recorder information from 177 frontal impacts, of which 23 with an overlap less than 30%.

Apart from the crash recorder information, injury data were collected and coded according to the Abbreviated Injury Scale (Association for the Advancement of Automotive Medicine, 1985), AIS85, with body localisation and injury type added. Belt use has been verified from interior inspections, and collisions involving unrestrained drivers, in total around 5%, were excluded from the study.

The impact severity parameters used in this study were change of velocity, mean and peak accelerations. In the distributions of accidents, the data were split in intervals for the included impact severity parameters. The injury risks were calculated for each interval, and smooth curve fits were used.

The crash test performed in this study was a two-car straight frontal collision with 28% overlap. The test speed was 58 km/h for each vehicle. The tested vehicles were a Saab 9000, 88 year model, and a Ford Scorpio, 87 year model. The test masses of the vehicles were 1420 kg for the Saab and 1370 kg for the Ford. Acceleration time history were measured at the sill below the left and right B-pillar. An HIII, 50 percentile dummy was used in the test, where head and chest accelerations and femur forces were measured.

## RESULTS

### Real life data

Fig 1 shows the distribution of frontal impacts with an overlap more than 30% and less than 30% at different change of velocities based on results from crash pulse recorders. The average  $\Delta V$  for the frontal impacts with high overlap was 22.4 km/h, while it was 19.4 km/h for the impacts with low overlap. The average mean acceleration was 6.0 g for the high overlap impacts and 5.5 g for the low overlap impacts, and the average peak acceleration was 15.7 g for the high overlap impacts and 20.0 g for the low overlap impacts.

Twentytwo per cent of all frontal impacts included in the accident data in this study had an overlap below 30%. Sixteen per cent of the injured drivers in frontal impacts, had injuries more severe than MAIS 2 and 5% more severe than MAIS 3. Table 1 shows that there were 24% MAIS2+ injuries with an overlap below 30%, while there were 14% in impacts with an overlap exceeding 30%. The corresponding numbers for MAIS3+ injuries were 9% and 4%.

Thirtythree per cent of all moderately or severely injured drivers and 42% of the severely injured drivers were injured in impacts with an overlap below 30%. Table 2 shows the correlation between MAIS and  $\Delta V$  in impacts with an overlap below 30%, where  $\Delta V$  was measured with a crash pulse recorder. The MAIS2 injury at lowest  $\Delta V$  occurred at a  $\Delta V$  of 14 km/h and the MAIS3 injury at lowest  $\Delta V$  occurred at a  $\Delta V$  of 27 km/h.



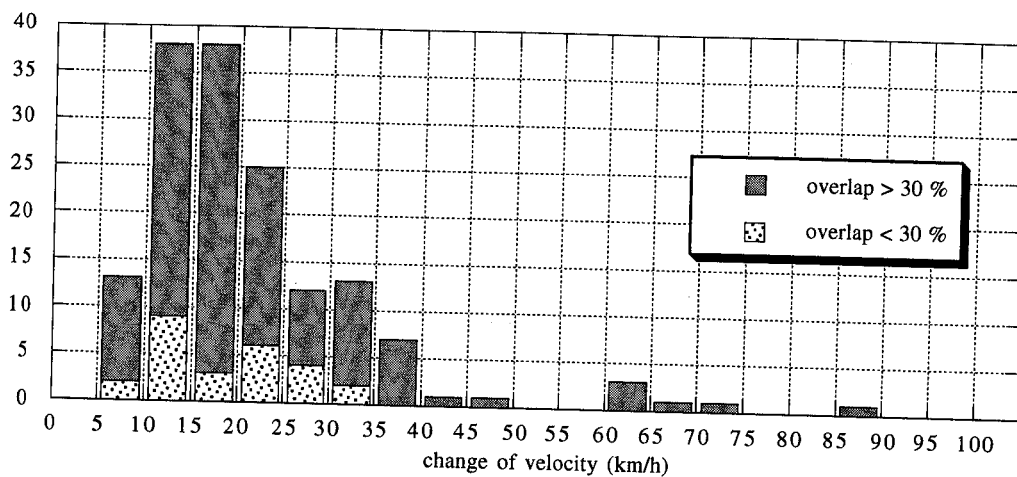


Figure 1. Number of impacts with an overlap more and less than 30% at different  $\Delta V$ 's.

Table 1.  
Number of drivers with MAIS 2+ and MAIS 3+ injuries, versus overlap

Overlap classification	Restrained drivers number (%)	MAIS 2+ number (%)	MAIS 3+ number
<30%	55 (22)	13 (33)	5
≥30%	190 (78)	26 (67)	7
Total:	245 (100)	39 (100)	12

Table 2.  
Number of driver injuries at different MAIS levels and measured  $\Delta V$  in impacts with an overlap below 30%, n=23

MAIS for each body region	$\Delta V$ (km/h)							
	0-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40
MAIS 0	-	-	4	1	4	1	-	-
MAIS 1	-	-	3	4	7	7	5	-
MAIS 2	-	-	2	1	1	3	-	1
MAIS 3	-	-	-	-	-	2	-	1
MAIS 4	-	-	-	-	-	-	-	1
MAIS 5	-	-	-	-	-	-	-	1

Table 3.  
Number of head and leg injuries, MAIS 2+ and MAIS 3+, for driver and front seat passenger, in frontal collisions with an overlap less than 30%

	Occupants	Head		Leg	
		MAIS 2+	MAIS 3+	MAIS 2+	MAIS 3+
Driver, near side	13	4	2	7	2
Front seat passenger, far side	9	1	0	2	0

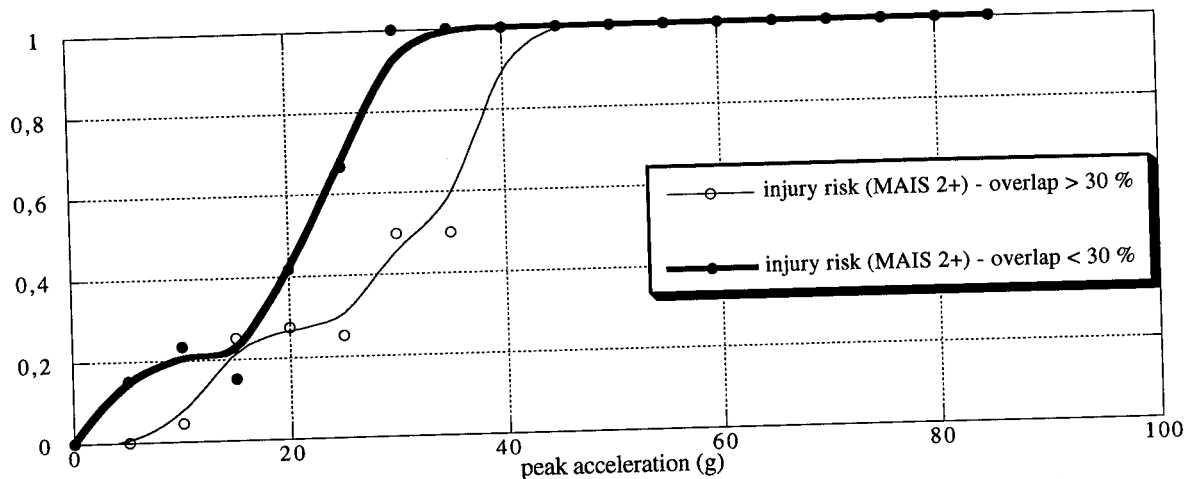
**Table 4.**  
**Number of injuries to drivers (near side) at different AIS levels to different body regions in frontal collisions, overlap less than 30%**

Body region (driver)	AIS1	AIS2	AIS3	AIS4	AIS5
Head	10	3	1	1	1
Neck	18	-	-	-	-
Arm	10	5	1	-	-
Leg	10	6	2	-	-
Back	10	-	-	-	-
Chest	7	4	1	1	-

Table 3 shows that there were lower numbers of moderate and severe injuries for the front seat passenger at far side, than for the driver at near side in impacts with an overlap below 30%. Table 4 shows that the dominating injuries in these impacts were head, leg and chest injuries.

Fig 2 shows that the injury risk for impacts with low overlap is significantly higher than for impacts with high overlap. At a peak acceleration of 30 g there is 50% risk of a severe injury in high overlap impacts while it is approximately 100% in impacts with low overlap.

Table 5 shows specific accidents presented in depth. The included accidents are frontal two-car impacts with an overlap of between 25% and 30%. The change of velocity of the studied impacts varied between 27 km/h and 39 km/h. The injuries varied from MAIS1 to MAIS5. The performance of the included vehicles differed a lot, especially considering the amount of intrusion. In some cases there were significant intrusion in one of the two vehicles and low in the other. The accidents are presented in the appendix.



**Figure 2. Injury risk (MAIS 2+) versus peak acceleration for impacts with an overlap more and less than 30%.**

**Table 5.**  
**Accident cases with an overlap of approximately 30 %**

accident	Case vehicle				Collision partner		
	Make and model	overlap (%)	$\Delta V$ (km/h) measured	MAIS driver	Make and model	$\Delta V$ (km/h) estimated	MAIS driver
1	Toyota Carina E -92	30	39.1	5	Volvo 244 -82	40	5
2	Toyota Camry -98	25	34.9	1	Saab 99 -82	45	5
3	Toyota Corolla -92	25	27.2	3	Opel Kadett -83	30	5

## Crash test results

Fig. 7 and 8 shows crash pulses for the two vehicles in the frontal crash test with 28 % overlap. The test speed was 58 km/h for each vehicle, while the change of velocity was 22 km/h for the Saab and 24 km/h for the Ford. There was a significant difference in both exterior

and interior deformation. The Saab 9000 had no intrusion in the footwell area while the Ford Scorpio had significant intrusion. Table 10 shows that the dummy measurements were low for both vehicles. The severity of the crash test was thus in the lower spectrum of the impact severity compared to the presented real life cases.

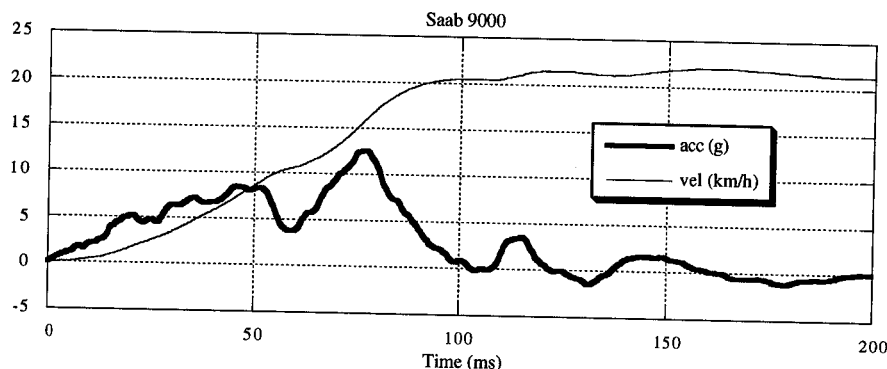


Figure 7. Crash pulse and change of velocity for the Saab 9000.

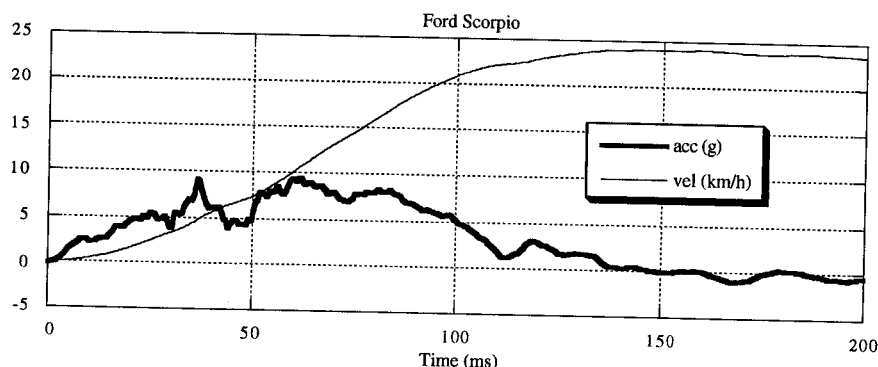


Figure 8. Crash pulse and change of velocity for the Ford Scorpio.

Table 10.  
Measurements from the crash test in 58 km/h, 28% overlap

Test vehicle	Car body			HIII driver			
	$\Delta V$ (km/h)	mean acc (g)	peak acc (g)	Head res (g)	Chest res (g)	Femur L (kN)	Femur R (kN)
Saab 9000 -88	22	3.5	12.6	19	27	0.8	-
Ford Scorpio -87	24	3.8	9.4	48	24	2.4	1.6



Fig. 9. The Saab 9000 and the Ford Scorpio in the crash test.

## DISCUSSION

Impacts with an overlap less than 30% produce a lot of severe injuries according to several studies (O'Neill, 1994; Thomas, 1994; Thomas, 1995). In this study 22% of all frontal impacts had an overlap below 30%. A study by O'Neill (1995) shows a corresponding number of 21%. There are, however, significant higher numbers of severely injured occupants in impacts with low overlap compared to impacts with high. As shown in Table 1, the proportion of moderate or severe injuries are higher in impacts with an overlap below 30%.

Severe narrow offset impacts are characterised by a high closing velocity, while the change of velocity could be relatively low. They are often connected with large intrusion and high intrusion velocity. Closing velocity is one impact severity parameter probably better correlated to injury risk than for example change of velocity. Intrusion velocity would probably be the parameter best correlated to injury risk if possible to measure or estimate. From Fig. 2 it is shown that other impact severity parameters than peak acceleration influence the injury risk for the driver at intrusion position. When plotting mean acceleration and  $\Delta V$  versus injury risk, a similar difference between low and high overlaps can be seen. This also results in that the outcome for a driver, near side, and a front seat passenger, far side, is very different.

In reconstructions of collisions are often  $\Delta V$  or EES used as impact severity parameters. Most reconstruction methods will give large errors in  $\Delta V$  calculations in impacts with glance-off, mainly because the impact type is not applicable for most reconstruction programs, but also because  $\Delta V$  sometimes is used synonymously with EES (Zeidler et al., 1997). Change of velocity calculated from the EES of the involved vehicle or vehicles will be too high since the energy needed to obtain a certain  $\Delta V$  in an impact with glance-off is higher than if the vehicle would stop to 0 km/h with the same  $\Delta V$ . If only one vehicle is available after an accident with two vehicles involved, a relevant reconstruction will be impossible to obtain. To be able to get a reliable change of velocity in an impact with glance-off, on board measurement technique is necessary. To be able to have relevant impact severity measurements in these impacts it is important to estimate the closing velocity, or if possible intrusion velocity.

The closing velocity in the presented real life accidents were significantly higher than in the performed crash test. An increased closing velocity will increase the deformation, although the change of velocity could be the same. The severity of the crash test were in the lower spectrum compared to the severity of the real life impacts

causing moderate or severe injuries. This is also obvious when studying the dummy measurements compared to the injuries in the real life impacts.

In a two-car collision with glance-off, the two vehicles are in contact for a certain time period. During that time period the vehicles are decelerating to a certain final change of velocity. The time duration of the pulse can be obtained from the recordings from the crash pulse recorder. This means that the time while the two vehicles have been in contact is measured. If the length of the contact area of the involved vehicles is measured, it can be related to the time duration of the crash pulse. This gives the average relative velocity between the two vehicles during the impact phase, which together with the measured  $\Delta V$  provides a possibility to calculate the closing velocity. The closing velocity is probably the best parameter, possible to measure, for this impact type. The average closing velocity during the impact phase will in turn give a possibility of estimating the intrusion velocity. This must be further evaluated for the accident sample as well as in crash tests.

The performance in collisions with low overlap might vary between different vehicles. As shown in this study the difference can be substantial. The architecture of the frontal structure seems important for the performance in this type of impacts. The tested Saab 9000 has a large distance between the side members, while the Ford Scorpio has a more traditional structure with closer distance between the side members and a longitudinal mounted engine. It seems beneficial to have a widely distributed energy absorbing area in the front. This is also shown in the real life accident no.2, see appendix. Stiffer structure is also a fact to take into account considering the outcome in that accident.

The risk of intrusion in impacts with small overlap should also be considered for impacts with guard-rails and other road side objects.

## CONCLUSIONS

- Impacts with an overlap below 30 % produce a lot of severe injuries.
- The frontal structure of vehicles is important for the performance in narrow offset impacts.
- Reconstructions of this type of impacts requires on board measurement technique.
- It is possible to estimate closing velocity in glance-off impacts from the recorded crash pulse and the length of the contact area.

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## APPENDIX

### Accident 1

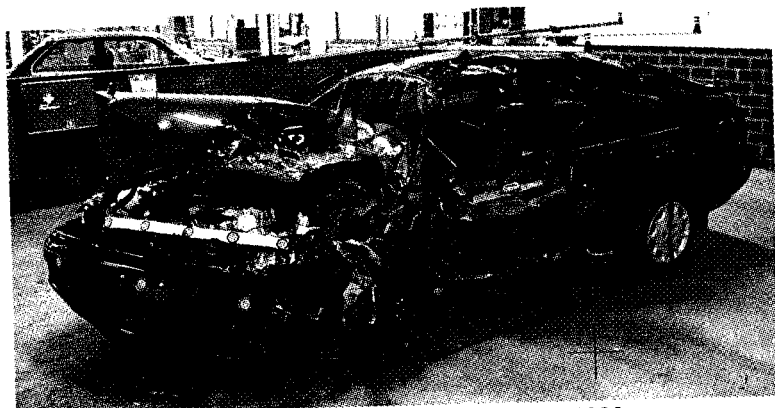


Figure 1. Case vehicle, Toyota Carina E, 1992.

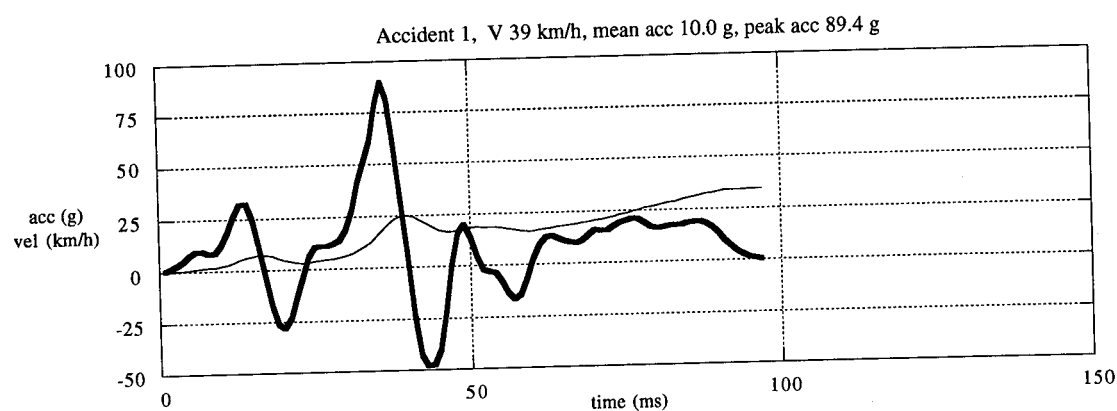


Figure 2. Crash pulse and change of velocity for the Toyota Carina E in accident 1.

Table 1.  
Occupant injuries, MAIS, in accident 1

Body region	Case vehicle		
	Pos 1 belted	Pos 2 belted	Pos 5 unbelted
Face / head	5	-	1
Neck	-	-	-
Arm	3	1	-
Leg	2	-	1
Pelvis	-	-	-
Back	-	-	-
Chest	4	1	-
Abdomen	-	-	-

Partner
Pos 1 unbelted
5(dead)
-
1
2
-
-
3
-

## Accident 2

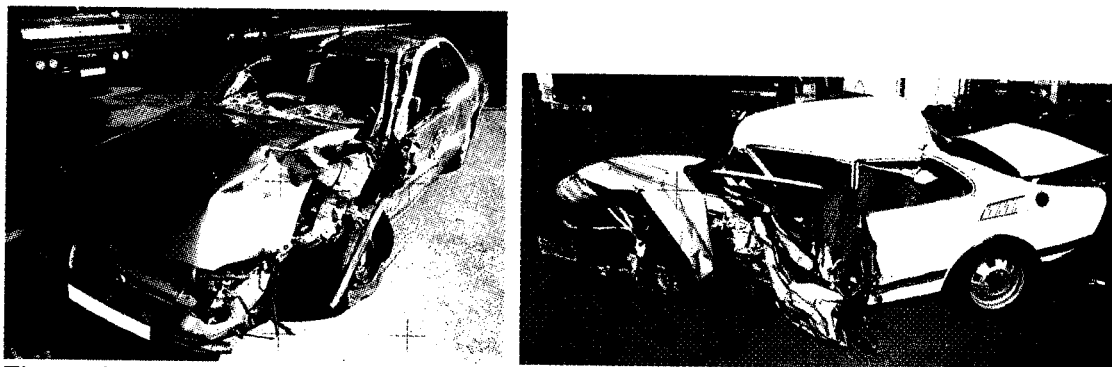


Figure 3. Case vehicle, Toyota Camry, 1997 and collision partner, Saab 99, 1982.

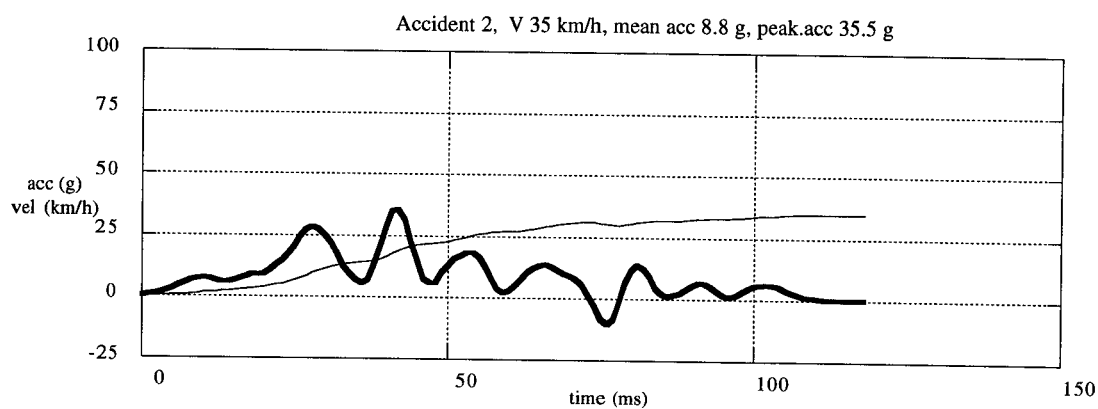


Figure 4. Crash pulse and change of velocity for the Toyota Camry accident 2.

Table 2.  
Occupant injuries, MAIS, in accident 2

Body region	Case vehicle	Collision partner	
	Pos1 belted	Pos 1 belted	Pos 2 belted
Face / head	1	4	3
Neck	1	-	-
Arm	1	3	2
Leg	-	3	2
Pelvis	1	3	-
Back	1	5	-
Chest	-	6 (dead)	5 (dead)
Abdomen	-	4	4

### Accident 3



Figure 5. Case vehicle, Toyota Corolla, 1992.

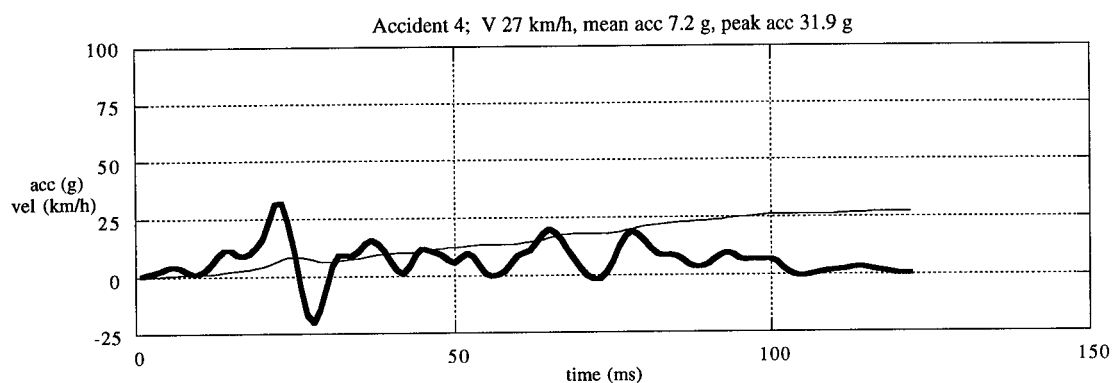


Figure 6. Crash pulse and change of velocity for the Toyota Corolla in accident 3.

Table 3.  
Occupant injuries, MAIS, in accident 3

Body region	Case vehicle			Partner	
	Pos 1 belted	Pos 2 belted	Pos 5 belted	Pos 1 belted	Pos 2 belted
Face / head	-	-	-	?	2
Neck	1	-	-	?	-
Arm	-	2	1	?	1
Leg	3	2	1	?	-
Pelvis	-	-	-	?	-
Back	1	-	1	?	-
Chest	2	2	1	5(dead)	-
Abdomen	-	-	-	?	-



# COMPATIBILITY STUDY IN FRONTAL COLLISIONS - MASS AND STIFFNESS RATIO

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## ABSTRACT

Compatibility of vehicles of different mass and stiffens in head-on collisions is studied in this paper with the aid of an eight-degrees of freedom, two dimensional lumped-mass simulation model. The model takes into consideration mass and stiffness ratio as the main factors contributing to compatibility of the two colliding vehicles. Other factors like length of crumple zone, offset overlap and speed are also considered. Three injury risk criteria have been considered in this study; delta V or change in velocity of vehicle after impact, maximum acceleration sustained by the passenger compartment throughout impact, and length of deformation sustained by the car front. The most crucial compatibility parameter is the mass ratio for the delta V criterion. The second and third compatibility parameters are mass ratio and stiffness ratio for deformation length criterion. A longer crumple zone is proposed for heavier vehicles to provide the required protection for smaller vehicles involved in head-on collision. It was found that both mass and stiffness ratio have no aggressivity on the partner vehicle when maximum acceleration criterion is used at low impact speeds.

## INTRODUCTION

The safety of car occupants does not only depend on the safe design of the car they ride, but depend also on the aggressivity of the design of the partner car involved in head-on collision. An aggressive design may provide good protection to the car in question and pose a threat to occupants of the other car involved in the collision. This raises the question of compatibility between vehicles where the level of protection of the occupants of a certain vehicle does not only depend on its crashworthiness performance, but on that of the other car too. The

problem of compatibility is a problem of mass, structural and geometrical interaction between the two colliding vehicles.

The question of compatibility between vehicles involved in frontal collisions has been revitalised in Europe. Recent development has introduced the concept of the ultra small and light vehicle for economic and environmental reasons. This development coupled with alarming fatality rate of car-to-car accidents has brought the problem of compatibility - i.e. safety implication when large and small cars collide together - into the forefront. European statistics indicate that 60-65% of fatalities in truck accidents are car occupants. Some 4200 of them die every year in car-to-truck frontal collisions. Some 2900 die yearly in car-to-car frontal collisions.

Despite publication of numerous research programme on compatibility, conflicting claims are being made regarding various factors affecting compatibility and aggressivity of road vehicles. It is generally accepted that injury risk to the occupants is higher in lighter vehicle involved in head-on collision with larger one. This is considered so on the basis of the effect of mass ratio between the two colliding vehicles. Because mass is a surrogate measure for other factors like size, shape, length of crumple zone and stiffness too, the effects of these individual factors on compatibility are overshadowed by the effect of the mass<sup>2</sup>.

It is envisaged that a comprehensive fast running simulation programme is required to achieve a thorough study involving all important factors affecting compatibility. This research focuses on the development of such a simulation programme, and to perform a thorough study and sensitivity analysis of main factors affecting compatibility of vehicle in head-on collisions. Mass and stiffness ratio are the main factors considered in this study. Other factors like length of crumple zone, offset overlap and speed are also considered. Geometric compatibility is not considered in this study. It is assumed that the two colliding structures geometrically interact with each other.

## MATHEMATICAL MODEL

The objective of the model is to enable quick simulation of the crush process and allow at the same time independent variation of important parameters that might influence compatibility. The parameters to take into consideration are: mass, stiffness, crash overlap, engine mass and engine location. A two-dimensional

lumped-mass model using two stage deformations is used in this study.

The full model include vehicle mass, engine mass and front assembly structure mass for each of the colliding cars. Two levels of plastic springs is assumed on both sides of the engine. The left and right longitudinal are replaced with plastic spring to simulate plastic deformation of the structure. Figure 1 shows all masses and stiffness elements for both cars.

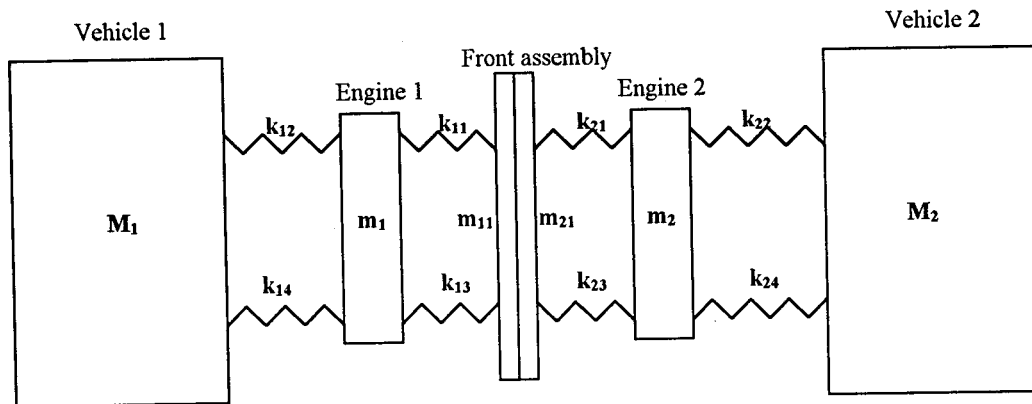


Figure 1 Schematic model of the crush system

The stiffness rates of the right and left hand sides are taken to be symmetrical for both cars. For each car, the two levels of 'spring' stiffness are increasing with deformation distance. Combining the primary stiffness  $k_{11}$ ,  $k_{13}$ ,  $k_{21}$ ,  $k_{23}$  and the secondary stiffness  $k_{12}$ ,  $k_{14}$ ,  $k_{22}$ ,  $k_{24}$ , the overall force displacement characteristics for a 'standard specification' car (total mass 1500 kg) has primary stiffness and secondary stiffness. One input for the stiffness value for each car was used to determine both primary and secondary stiffness. The deformation displacement points were fixed. Although stiffness and mass distribution are symmetrical, an asymmetrical impact (overlap  $<1$ ) produces asymmetrical loading and hence asymmetrical deformation for both cars. The front assembly parts,  $m_{11}$  &  $m_{21}$ , act as a rigid body of two masses stuck together, therefore providing a mechanism of load transfer from one longitudinal 'spring' to the other.

The primary part of the stiffness curve is a lower rate stiffness for the first 270 mm of deformation, followed by higher stiffness rate for the next 80 mm of deformation - before reaching the end of engine

deformation zone at 350 mm. The secondary deformation zone starting at 350 mm is a constant deformation force (zero rate) for the rest of the deformation zone. The simulation solves 24 equations and 24 unknowns:

$$\begin{aligned} &X, \theta, X_1, \theta_1, X_2, \theta_2, X_{15}, X_{25} \\ &F_{11}, F_{12}, F_{13}, F_{14}, F_{21}, F_{22}, F_{23}, F_{24} \\ &X_{11}, X_{12}, X_{13}, X_{14}, X_{21}, X_{22}, X_{23}, X_{24} \end{aligned}$$

Initial conditions for all masses, except for  $m_{11}$  and  $m_{21}$ , were assumed to be that of impact velocities of the vehicles. The central bumper assembly masses  $m_{11}$  &  $m_{21}$  were assumed to be in contact throughout the crush process and have a unified velocity and displacement. Its initial velocity is calculated using momentum equation of two masses colliding head-on with zero coefficient of restitution

## CRASH SIMULATION

Various combination of mass ratio, stiffness ratio, impact speed ratio have simulated. Crash displacement, impact speed ratio have simulated. Crash displacement, passenger compartment acceleration, 'spring' forces have been plotted versus time to check and validate the simulation results. Standard data have been tried as well as comparison with other published work <sup>(5), (13)</sup> to validate the simulation. Typical simulation results of

acceleration, displacement and force versus time are shown in figures 2 and 3 and 4. Figure 5 also shows acceleration versus displacement curve.

The simulation results show quasi equilibrium crash dynamics when ignoring effective mass of the structure. Only variation in stiffness is taken into consideration thus eliminating any high frequency oscillation from the results. The simulation data are that of 15 tons vehicle versus 1.5 tons both colliding at 30 mph speed 100% overlap.

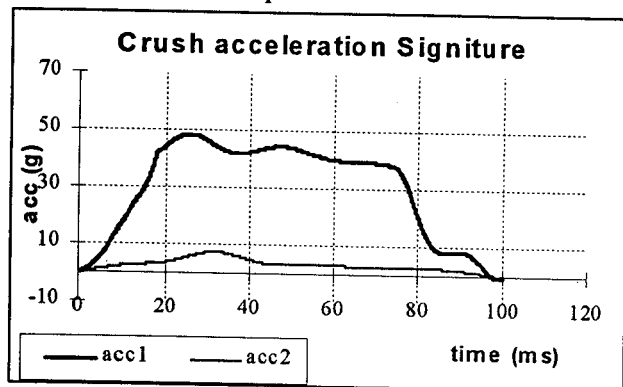


Figure 2 Crash acceleration signature

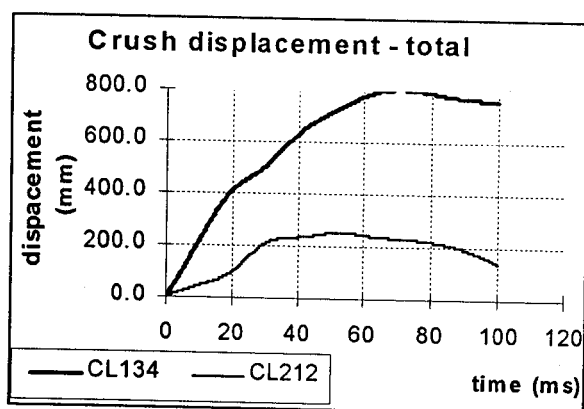


Figure 3 Crash deformation signature

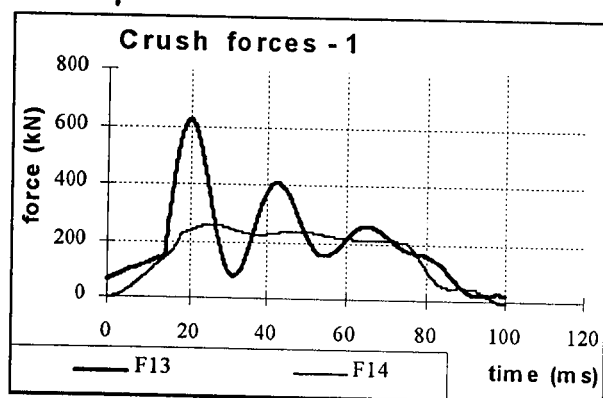


Figure 4 Primary and secondary forces

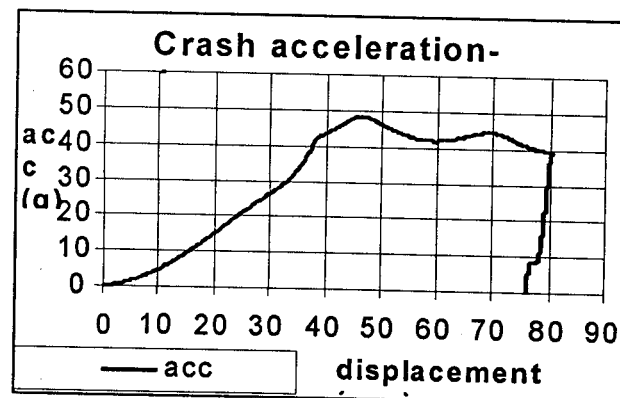


Figure 5 acceleration versus displacement

## INJURY RISK CRITERIA

Various criteria have been used by different researchers ranging from the maximum or average acceleration of the passenger compartment, to the length of deformation attained during the crash. Other criterion involved occupants kinematics model by calculating acceleration and speed of various parts of the torso up to the time of the secondary impact between the occupant and car interior. The question of modelling the occupant's motion has been ruled out on the ground of the accuracy required. Three criteria have been identified as most relevant for this purpose;

- i) Delta V change sustained by each vehicle at the end of the crash.
- ii) Maximum acceleration sustained by the passenger compartment during the crash.
- iii) Maximum length of deformation sustained by the frontal structure of the car.

The weightings of these criteria are believed to depend mainly on the closing collision velocity at the moment of impact. It can be said that the first criterion - delta V is more relevant at lower closing velocities than the other two criteria as acceleration and deformation length are not expected to attain critical levels. At intermediate closing velocities the second criterion - maximum acceleration becomes more relevant, whilst the third criterion - deformation length is relevant at high closing velocities only. What define the boundaries of these closing velocity categories depend on the combination of three design parameters: mass, stiffness and crumple zone. It is therefore considered that all these criteria are important to be considered and treated in the priority cited above.

### Mass ratio compatibility

The first parameter investigated was mass ratio with regard to all three injury risk criteria. Figures 6, 7 and 8 show variation of injury criteria with mass ratio ranging from 0.5 to 10. Stiffness characteristics were assumed standard for both vehicles while offset overlap were taken to be 100%. Initial velocities for both vehicles were fixed at 13.33 m/s (30 mph). Vehicle 1 is the standard fixed characteristics vehicle while vehicle 2 is the varied characteristics one. Compatibility is measured on changes in injury criteria of the standard vehicle (no 1) due to variation in characteristics of the partner vehicle (no 2).

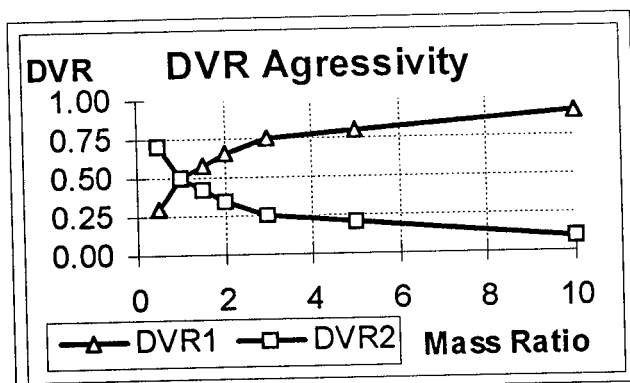


Figure 6 delta V ratio versus mass ratio

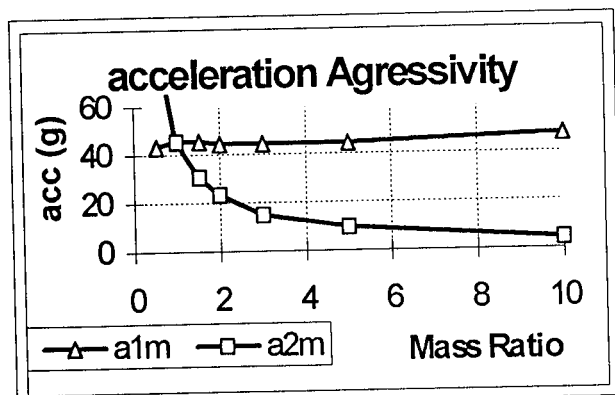


Figure 7 maximum acceleration versus mass ratio

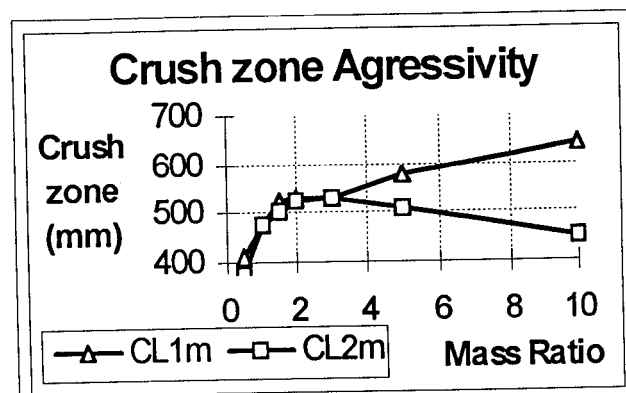


Figure 8 Deformation versus mass ratio

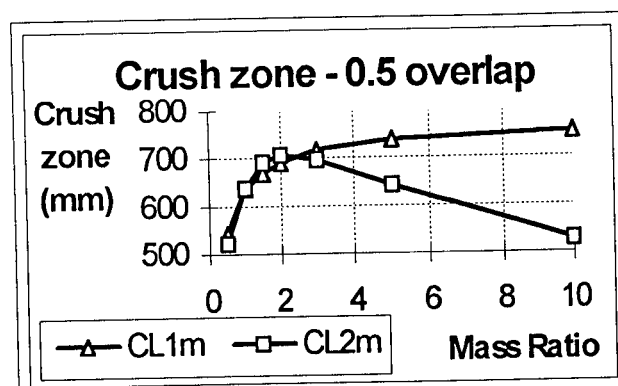


Figure 9 Deformation versus mass ratio

Figure 6 shows clear aggressivity of mass ratio for the delta V criterion. This is a direct implication of the momentum laws that result in the lower mass vehicle enduring higher velocity change. Figure 7 shows very low aggressivity for the acceleration criterion because stiffness of both vehicles is the same. The maximum crush force causing the deceleration of both vehicles is not changed, and therefore acceleration of the standard vehicle (no 1) does not change with variation of the partner vehicle's mass. The latter would experience smaller acceleration with increasing mass as the maximum force is fixed in all cases. For offset crashes of 50% overlap, the behaviours of delta V and acceleration criteria are almost the same as that of 100% overlap. However, acceleration levels in offset crashes are slightly lower due to concentration of load on one longitudinal.

Aggressivity of the mass ratio for the deformation length criterion is clearly illustrated in Figure 8 with the increasing deformation length of the standard vehicle versus increasing mass ratio. The behaviour of the partner vehicle (no 2) is shown to increase first with the

mass ratio up to a ratio of about 3, beyond which deformation length of the partner vehicle decreases with mass ratio. This behaviour of the partner vehicle is attributed to energy absorption which become less for the higher mass vehicle. Since the first 350 mm of deformation has lower crush force, higher deformation length is expected in this region. For offset crashes of 50% overlap, aggressivity of mass ratio for the deformation length criterion is demonstrated to be lower than 100% overlap. This is clearly demonstrated in Figure 9 where little change in deformation length of the standard vehicle (no 1) is shown versus increase in mass ratio. This behaviour in offset crashes is attributed to the existence of load transfer mechanism between the two longitudinal 'springs', transferring deformation from the highly loaded longitudinal to the less loaded longitudinal in the region when deformation reaches about 700 mm. This behaviour demonstrates how homogenous distribution of stiffness across car front contributes to Compatibility in head-on crashes.

### Stiffness ratio compatibility

The second parameter investigated was stiffness ratio. Figures 10, 11, 12 and 13 show variation of injury criteria with stiffness ratio ranging from 0.5 to 6. The maximum ratio of 6 is dictated by the maximum possible rigid structure (equivalent maximum crush force of 1250 kN). Mass characteristics were assumed standard for both vehicles while offset overlap were taken to be 100%. Initial velocities for both vehicles were fixed at 13.33 m/s (30 mph). Vehicle 1 is the standard fixed characteristics vehicle, while vehicle 2 is the varied characteristics one. Compatibility is measured on changes in injury criteria of the standard vehicle (no 1) due to variation in characteristics of the partner vehicle (no 2).

Primary stiffness ratio  $k_{11}/k_{21}$ ,  $k_{13}/k_{23}$ , and secondary stiffness  $k_{12}/k_{22}$ ,  $k_{14}/k_{24}$  have been investigated separately. Very similar results were obtained for their effects on all three injury criteria. It was decided to lump the two stiffness ratios in one and vary both primary and secondary stiffness parameters at the same time and according to one common stiffness ratio input. Figure 10, 11 show the acceleration injury criterion versus stiffness ratio for 100% and 50% overlap respectively. For 100% overlap, Figure 10 shows that stiffness ratio has no acceleration aggressivity at all. This is the case because the maximum acceleration of the standard vehicle (no 1) stays constant at about 44 g regardless of the stiffness ratio. On the contrary higher stiffness of the partner vehicle increases acceleration injury risk of its own occupants as demonstrated in

Figure 10. For 50% overlap, Figure 11 shows that stiffness ratio has some level of acceleration aggressivity, particularly for ratio less than 3. This is clearly evident from the fact that the maximum acceleration of the standard vehicle (no 1) in figure 11 increases from 25 g, at a ratio of 0.5 to 40 g at a ratio of 3.

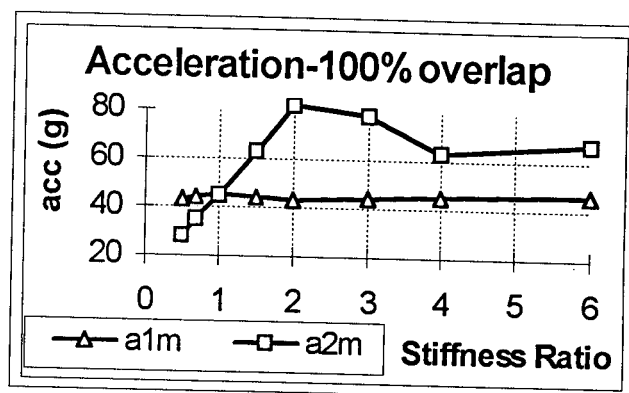


Figure 10 maximum acceleration versus stiffness ratio, 100% overlap

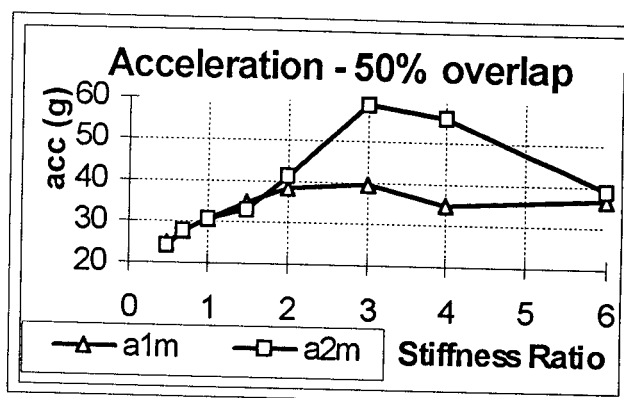


Figure 11 maximum acceleration versus stiffness ratio, 50% overlap

Stiffness ratio has no delta V aggressivity at all as far as the mass ratio remains constant. This is the case because the maximum delta V ratio (to closing velocity) of the standard vehicle (no 1) stays constant at about 0.5 regardless of the stiffness ratio. This behaviour is almost repeated for 50% overlap crashes. As for the deformation length criterion, Figure 12 (100% overlap) shows clear aggressivity of the stiffness ratio where the deformation length increases from 400 mm, at a ratio of 0.5, to 600 mm at a ratio of 6. Similar results are obtained for a 50% overlap crash.

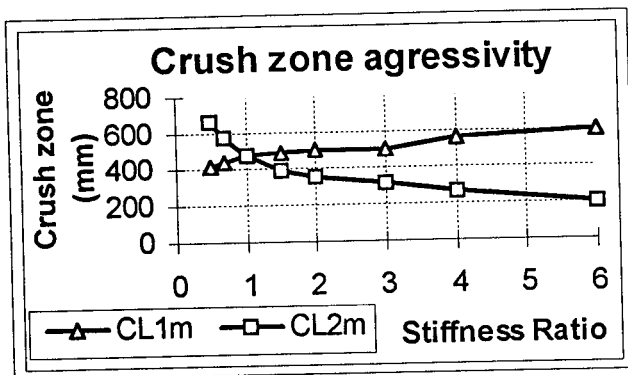


Figure 12 Deformation versus stiffness ratio

## SUMMARY AND CONCLUSIONS

The aggressivity of mass ratio and stiffness ratio for three injury risk criteria is summarised in Table 1. Aggressivity rating is given one of four scores; high, medium, low & none. Two scores are given for each category; 100% overlap and 50% overlap.

The most crucial compatibility parameter is the mass ratio for the delta V criterion. Nothing could be done about this incompatibility factor apart from geometric compatibility measures where structural interaction between the vehicles is prevented. The second and third compatibility parameters are mass ratio and stiffness

ratio for deformation length criterion. These two compatibility factors could be made to compensate for each other. A slightly softer and longer crumple zone is required for heavier vehicles to achieve this compatibility. As far as acceleration injury criterion is concerned, both mass and stiffness ratio have no aggressivity on the partner vehicle. Acceleration is determined by the vehicle's own mass and stiffness.

	Delta V	Acceleration	Deformation length
Mass ratio	High	None	Medium
Stiffness ratio	None	None	Medium

Table 1 Summary of aggressivity 100% overlap

	Delta V	Acceleration	Deformation length
Mass ratio	High	None	Low
Stiffness ratio	None	Low	Medium

Table 2 Summary of aggressivity rating 50% overlap

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# THE EFFECT OF HYBRID III LOWER LEG KINEMATICS ON LOADING MECHANISMS AND INJURY CRITERIA

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## ABSTRACT

With the ever increasing survivability of road traffic accidents due to the introduction of airbags, and the proposed implementation of the new European Frontal Impact Legislation, motor manufacturers are now focusing on reducing lower limb injuries. To achieve this, there is a need to develop a better understanding of lower leg injury mechanisms, and lower leg interaction with the intruding footwell.

An industry collaborative group was established, which included Ford, Jaguar and Rover, with the research being managed by the Motor Industry Research Association MIRA. The Lower Leg Injuries and Methods of Prevention (LLIMP) Vehicle Design Project was to focus on footwell and restraint system design. A program of crash tests, including both Front fixed Barrier and Offset deformable tests were conducted and an evaluation of the analysed results from lower leg and footwell instrumentation was conducted. This identified five distinct phases in lower leg kinematics, which are affected by both the footwell intrusion profiles and Hybrid III dummy lower leg positions and geometry. The interaction of the dummy lower leg and the foot have also been investigated using HyGe sled test techniques, with both static and dynamic intruding footwells.

The paper presents the five phases of lower leg kinematics, plus the interaction between the dummy foot and footwell on the lower leg kinematics. The paper will then investigate the options for controlling these for reducing lower leg injury criteria.

## INTRODUCTION

Lower leg injuries to car occupants are relatively common in road traffic accidents. As a result of legislation already in place to reduce injury through seat belts and the use of airbags there has been a significant improvement in passenger survival in road

traffic accidents. There continues to be however a significant level of disabling lower leg injuries as a result of footwell intrusion.

Motor manufacturers are now focusing on improving the safety of car occupant, particularly in relation to lower leg injury, especially with the proposed implementation of the new European Frontal Impact Legislation, European Directive 96/79/EEC, which includes the use of Hybrid III crash dummies and lower leg injury criteria.

The Lower Leg Injury and Methods of Prevention LLIMP Project is devised to link the injuries from road traffic accidents with the kinematics and loading mechanisms experienced by Hybrid III dummies in crash tests. The LLIMP project consists of two individual research projects, Biomechanics and Vehicle Design, working independently but in parallel. While the Biomechanics Project is researching actual lower leg injuries and injury mechanisms, the Vehicle Design Project is investigating the kinematics and loading mechanisms in the Hybrid III lower leg in view of better vehicle structural, pedal and footrest design. The Vehicle Design Project is an industrial collaborative project sponsored by Rover Group, Ford Motor Company and Jaguar Cars and the research managed by the Motor Industry Research Association (MIRA). In a phased approach the project has conducted a programme of frontal crash tests using enhanced lower leg and footwell instrumentation in order to achieve a better understanding of lower leg kinematics and loading mechanisms. Development of a finite element computer model of the lower leg correlated to component, system and crash test data is being used to evaluate the sensitivity of the Hybrid III lower leg for different footwell impact scenarios to improve footwell, pedal and footrest design. Although concentrating in the initial phases on the current Hybrid III instrumented lower leg, as specified in the new European legislation, the performance and sensitivity

of advanced Hybrid III lower legs will be evaluated in later phases.

The paper presents the initial phase of the project in which the lower leg kinematics and loading mechanisms from the baseline crash tests have been analysed and how these affect lower leg injury criteria.

## LOWER LEG AND FOOTWELL INSTRUMENTATION USED IN THE FRONTAL CRASH TESTS

The data from the instrumented Hybrid III lower legs has been analysed from over 20 crash tests. These have included results for driver and passenger lower legs in both offset deformable and front fixed barrier crash tests with standard and enhanced levels of lower leg and footwell instrumentation.

### Lower Leg Instrumentation

The instrumented Hybrid III lower leg, prescribed in the European Frontal Legislation (96/79/EEC) is used to assess potential lower leg injuries. The lower leg, shown in Figure 1, is essentially a steel skeleton with ball joints at the hip and ankle, and a pin joint at the knee. The individual steel sections are covered with a vinyl outer flesh, being used in combination to produce the correct anthropometric static and dynamic characteristics. The lower leg injury criteria, Upper and Lower Tibia Index, used to assess the probability of a complex tibia fracture, and Tibia Compressive Force Criterion (TCFC), fracture to the tibia at the Knee and Ankle joints, are calculated from the loads generated in the tibia. These are measured at load cells located at the top and bottom of the tibia shaft, the European directive requiring the measurement of two bending moments  $M_y$  and  $M_x$ , plus the Axial Force  $F_z$ .

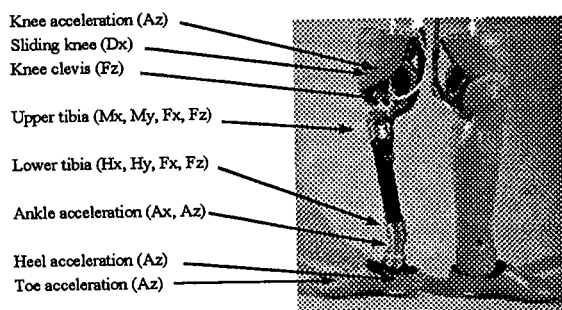


Figure 1 Lower Leg Instrumentation

As a major part of the LLIMP project was to gain a better understanding of lower leg kinematics, lower leg 4 axis load cells were supplemented with accelerometers mounted in the toe, heel, lower tibia (immediately above the ankle) and the upper tibia (immediately below the knee). In the majority of the baseline tests uniaxial accelerometers were located at the toe, heel and knee in the axial direction with Biaxial in axial and longitudinal directions at the ankle. However triaxial accelerometers can be located at all these locations from which the 3-dimensional motion of the lower leg can be analysed.

### Footwell Instrumentation

In order to evaluate the dynamic deformation of the footwell, an array of instrumentation was used; Figure 2 showing the typical instrumentation specification. Accelerometers were located on the brake and accelerator pedals, plus close to the toe and heel impact points to both inboard and outboard feet. These were used to define the main toe and heel impact times and magnitudes, as well as impacts, between the footwell and rigid components in the engine bay. However, as the accelerometers were in a deforming part of the vehicle structure, and changed orientation during the impact, integrated footwell velocities and displacements should be used with extreme caution. To accurately assess dynamic floor displacements potentiometers can be used, even with dummies installed.

Dynamic intrusions were measured at both the bottom and top of the footwell; the lower intrusion producing the footwell translation, while the upper intrusion when taken from the lower, footwell translation produced the footwell rotation. Although these only gave the intrusion profile at the centre of the footwell; pre- and post-test static measurements were used to evaluate the deformation at all points in the footwell, while accelerometers gave an indication of the timing of the intrusion. Without dummies, an increased array of potentiometers can be used, so a 3-dimensional map of footwell deformation can be produced.



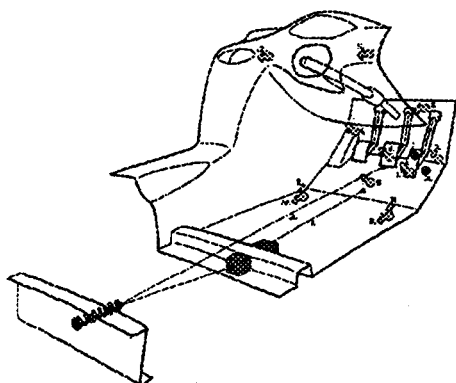


Figure 2 Footwell Instrumentation

## ANALYSIS OF LOWER LEG KINEMATICS

In order to evaluate lower leg kinematics and loading mechanisms in frontal crash tests five main phases of lower leg kinematics have been proposed after analysing results from baseline crash tests. These proposed phases have been formulated as follows and are shown in Figure 3:

- Phase 1 - Toe Contact
- Phase 2 - Heel Contact
- Phase 3 - Ankle Rotation
- Phase 4 - Lateral Ankle Lock-up
- Phase 5 - Longitudinal Ankle Lock-up

As such the phases existence and length vary greatly dependent on the vehicle crash test scenario and lower leg orientation and location. For each of these kinematic phases the loading mechanisms have been evaluated and the relative magnitude of the forces, bending moments and accelerations derived.

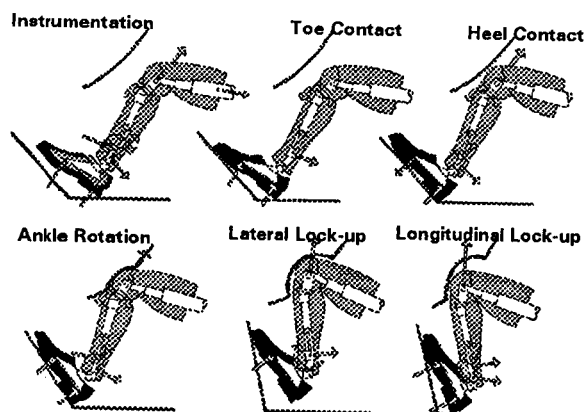


Figure 3 Lower Leg Kinematic Phases

### Phase 1 - Toe Contact

On initial impact with the barrier, the vehicle starts to decelerate, so the occupant moves forward relative to the vehicle. The whole leg 'slides' forward either depressing the accelerator pedal or moving towards a footrest or footwell. (Analysis of crash tests have shown that in most cases the foot moves slightly rearward under the initial acceleration of vehicle run-up pulling the foot off the footrest or footwell producing a gap which has to close before toe contact).

The toe then impacts the footwell or footrest directly, or the accelerator pedal 'bottoms-out' on its end stop causing the toe to rapidly accelerate. However as the lower leg and heel are still moving forward the foot has to rotate round the ankle, in dorsiflexion, producing low axial loads and tibia bending moments.

### Phase 2 - Heel Contact

On heel impact with the footwell, the heel rapidly accelerates, making the foot momentarily rotate in plantarflexion reversing the toe acceleration. Due to the heel's proximity to the ankle the acceleration affects the whole tibia producing ankle accelerations and lower tibia Fx and Fz loads as the heel and ankle are accelerated to the footwell velocity. With the pelvis and knee still moving forward relative to the footwell, the tibia has to rotate about the ankle and knee and therefore undergoes angular acceleration producing an upper tibia My bending moment. If the relative velocity between the heel and footwell is large then the combination of the higher axial load Fz and upper Tibia, My, produces upper Tibia Index peaks. These being inertia loading mechanisms.

### Phase 3 Ankle Rotation

With the foot now in full contact with the footwell and the tibia rotating about the knee and ankle as the pelvis continues to move forward, both lower leg accelerations and loads reduce from those produced in Phase 2. Phase 3 will continue until either the ankle rotation has reached its limit causing 'ankle lock-up', or the knee or tibia impacts the lower dashboard changing the inertia loading mechanism to quasi-static.

### Phase 4 Lateral Ankle Lock-up

Lateral ankle lock-up usually only occurs for the driver, where the feet are located on pedals or footrests. If the foot is not centrally located on the pedal or footrest, or there is lateral motion of either, the heel 'slips off' producing ankle rotation in either inversion or eversion. With the maximum lateral ankle rotation of 30 degrees, lateral ankle lock-up can occur rapidly,

producing an instantaneous rise in both upper and lower tibia Mx bending moment. The loading mechanism changes from inertial to quasi-static.

Pure lateral ankle lock-up is not normally accompanied by a rise in the longitudinal bending moment. However, as the ankle continues to move forward, the ankle stop contact surface will rotate from a lateral to a combined lateral / longitudinal direction which produces a gradual rise in the My bending moment, particularly in the lower tibia.

#### Phase 5 Longitudinal Ankle Lock-up

Longitudinal ankle lock-up occurs either from the ankle reaching its longitudinal rotational limit, from Phase 3, or by rotation of the ankle end stop surface following lateral ankle lock-up, in Phase 4. If pelvis to footwell relative velocity is still high or there is considerable footwell rotation at the time of longitudinal lock-up, then the lower tibia bending moment immediately rises producing a peak in the lower tibia index. The rapid rise in lower tibia index My bending moment is often followed by 'Heel Jump' in which the heel actually leaves the footwell, reducing the lower legs' loads before impacting with the footwell with another immediate rise in loads.

Following ankle lock-up the magnitude of Fz and My loads, and therefore upper and lower tibia index peak, depend on the amount of pelvis forward or footwell rearward motion left. In vehicles where lock-up occurs before large amounts of footwell intrusion the My bending moments can be considerable while if lock-up occurs at the limit of pelvis forward motion after footwell intrusion there will be a negligible increase.

### **APPLICATION OF KINEMATIC PHASES TO CRASH TEST DATA**

Two examples are now used to demonstrate how the proposed lower leg kinematic phases can be applied to lower leg test data.

- HyGe Sled Test with no dynamic intrusion
- Baseline Offset Deformable Crash Test

#### **HyGe Sled Test**

Although the primary purpose of a series of HyGe sled tests was to correlate the development of the lower leg finite element model it allows the lower leg kinematics to be observed and linked directly to loading mechanisms. Figure 4 shows the lower leg

accelerations and loads with the lower leg motion in each of the kinematic Phases. In this example the sled is given the B-post acceleration for a medium sized vehicle with the RH lower leg impacting a rigid footwell inclined at 60 degrees

#### Phases 1 & 2

As the foot was initially inclined at the same angle as the rigid footwell the toe impacts at 26 ms, only 4 ms prior to the heel impact, with a relative velocity of 5 m/s. Toe acceleration peaks before rapidly reducing with heel impact at 30 ms. Heel acceleration peaks at 32 ms with the lower tibia Fz and upper tibia My rising rapidly to peak at the same time. These are produced by inertia loading mechanisms accelerating the tibia in both translation and rotation. The combination of these causes the upper tibia index peak.

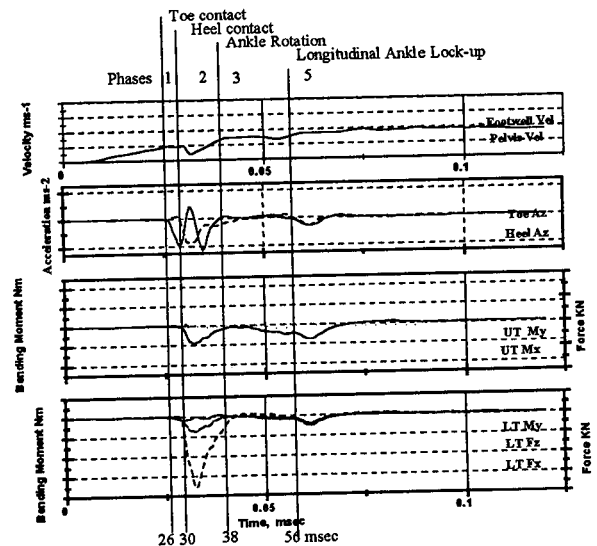


Figure 4 Lower leg test data. HyGe sled test

#### Phase 3

Ankle rotation occurs from 38 - 56 ms and with minimal inertial loading; all the accelerations and loads reduce to a minimum.

#### Phase 4

As the footwell is stable, with no feet stability problems, no lateral lock-up occurs and therefore Phase 4 is omitted.

#### Phase 5

Ankle rotation occurs until 56 ms when longitudinal lock-up occurs. As there is no dynamic footwell intrusion and the pelvis reaches its maximum forward

trajectory, shortly after lock-up, tibia axial loads and bending moments rise only gradually to peak at 61 ms producing the lower tibia index peak. These are produced by quasi-static loading mechanisms which actually load up the femur and slightly increases pelvis acceleration.

As can be seen the proposed Kinematic phases and associated loading mechanisms have been validated as the actual lower leg motion can be observed. In crash tests it is very difficult to directly observe lower leg kinematics so therefore the Phases are evaluated from the footwell and lower leg instrumentation data.

### Baseline Offset Deformable Crash Test

The second example, shown in Figure 5, shows the instrumentation data for a RH lower leg in a RH offset deformable crash test. With the foot on the accelerator pedal. All 5 kinematic phases are represented.

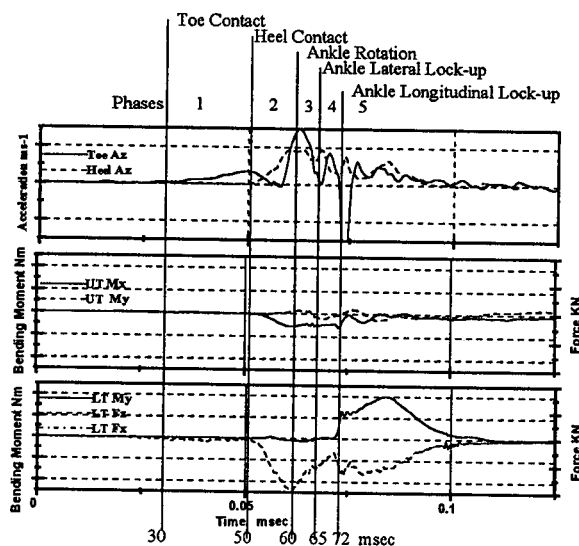


Figure 5 Lower leg test data - Baseline deformable crash test

#### Phase 1 Toe Contact

Accelerator pedal impacts the end stop at 30 ms producing a rise in toe acceleration as the foot starts to rotate.

#### Phase 2 Heel Contact

Heel impacts the footwell at 50 ms with rise in heel and ankle accelerations. Lower tibia Fz and upper tibia My and Mx rise under inertia loads producing the upper tibia index peak at 61 ms.

#### Phase 3 Ankle Rotation

After the peak inertia loads at 60 ms the lower leg accelerations and loads reduce under ankle rotation.

#### Phase 4 Lateral Ankle Lock-up

At 65 ms the ankle locks-up laterally in eversion, as the foot slips off the accelerator pedal inboard. This is identified by the reversal in the upper tibia Mx bending moment and slight increase in lower tibia My, indicating that the lock-up has a longitudinal component. Ankle rotation continues as the heel moves forward, the ankle stop contact surface rotates with an increasing longitudinal component.

#### Phase 5 Longitudinal Ankle Lock-up

At 72 ms the ankle locks up longitudinally while dynamic footwell intrusion occurs producing an instantaneous rise in lower tibia My. The lower tibia index peaks at 84 ms. As the loading mechanism changes from inertial to quasi-static the upper tibia My actually reverses, reducing the upper tibia index.

Application of the proposed kinematic phases to lower leg crash test data has assisted in evaluating the complex loading mechanisms which occur in the lower leg during the dynamic interaction between the feet and the footwell.

### EFFECT ON DIFFERENT LOWER LEG KINEMATICS ON LOADING MECHANISMS

The Kinematic Phase analysis technique has been applied to a large number of lower leg results from the LLIMP project baseline crash tests. These have highlighted several different types of lower leg kinematics and their associated loading mechanisms. The following 4 examples demonstrate how the Kinematic Phases are affected under differing impact environments.

#### High Footwell Intrusion Rotation and Translation

With rapid footwell translation and rotation occurring, while the foot is in contact with the footwell, the kinematic phases get compressed and several are omitted. Figure 6 shows the RH lower leg results for a small vehicle in a RH Offset Deformable crash test.

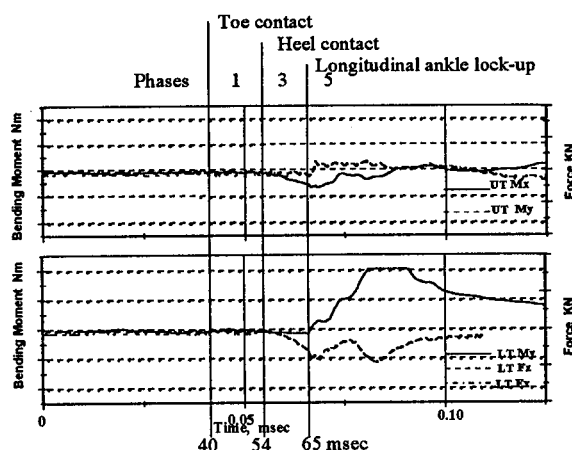


Figure 6 Lower leg test data - High Intrusion Rotation and Translation

Phases 1 and 2 are clearly defined with toe contact at 40 ms and heel contact at 54 ms, producing the rise in tibia axial loads. However before the lower leg translational and rotational accelerations peak under inertial loading, longitudinal ankle lock-up occurs at 65 ms, kinematic phase 5 starts, while phases 3 and 4 are omitted.

As already seen if longitudinal lock-up occurs during dynamic footwell rotation, the lower bending moment rises very rapidly producing a high lower tibia index which in this example occurs at 83 ms.

Analysis of the baseline crash tests have shown the importance of both the magnitude and timing of footwell translation and more particularly rotation on firstly causing ankle longitudinal lock-up and secondly high quasi-static loads. Reducing the amount of footwell rotation decreases the probability of lock-up occurring but also if the intrusion can be delayed or its rate reduced the loads produced after lock-up can be minimised.

### Wheelarch Footrest Design

In LHD vehicles the LH foot is often placed on a footrest directly attached to the wheelarch. In offset deformable crash tests the LH front wheel impacts directly on the wheel arch producing both rearward translation and rotation of the footrest. Two different types of footrests are normally used and these have

significant affect on the lower leg kinematics and loading mechanisms.

### Stable Footrest

Figure 7 shows the lower leg loading for a LH leg placed on a stable, relatively rigid footrest. After toe and heel contact, Phases 1 and 2, at 8 and 12 ms respectively, the foot remains on the footrest with minimal lateral movement. As the heel contact occurred early due to its initial proximity with the footrest, inertia loads are very low.

In Phase 3 (ankle rotation) there are several rises in Fz and upper My, which start at 54 ms, indicating the commencement of wheel arch intrusion producing a secondary increase in inertial loading. At 65 ms a combination of longitudinal and lateral ankle lock-up occurs as shown by the series of increases and decreases in all the bending moments as the heel moves in 'jerks' rearwards. At 85 ms heel rearward motion stops producing a rise in lower tibia My due to the quasi-static loading following lock-up.

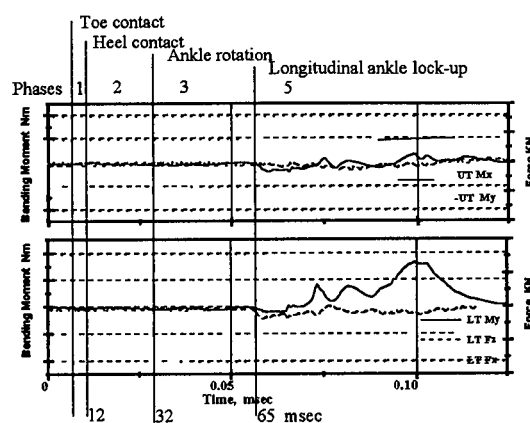


Figure 7 Lower leg test data - Stable left hand footrest

### Unstable Footrests

The other type of footrest used for the LH leg in LHD vehicles is a foam moulding which is located around the wheelarch, but not directly attached to it. This is located under the underlay and carpet with a flat plastic plate on the carpet outer. Figure 8 shows the lower leg results for such a footrest in an offset deformable barrier crash test.

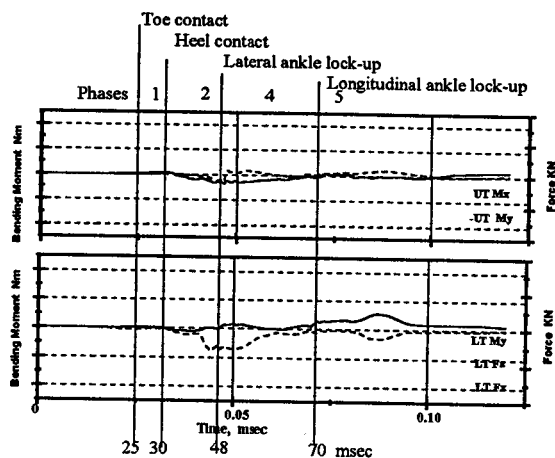


Figure 8 Lower leg test data - Unstable left hand footrest

As with the stable footrest, toe and heel contact occur early at 25 and 30 ms respectively. However under the initial impact the under carpet moulding rotates around the wheel arch causing the heel to move inboard with the ankle rotating in 'eversion'. As the heel continues to move laterally and forward, lateral ankle lock-up occurs at 48 ms. This can be identified by the rapid reversal in the upper tibia Mx bending moment as the loading mechanism changes from inertial to quasi-static in the lateral direction.

As seen before the lateral ankle lock-up does not produce a significant rise in the lower My bending moment. However as heel forward motion continues as it no longer has any support, total ankle lock-up occurs at 70 ms producing a peak in the lower tibia My bending moment and tibia index.

These two examples show how footrest design has a direct effect on the lower leg kinematics and loading mechanism. Stable footrests reduce the probability of lateral ankle lock-up, however, as forward motion of the foot is restricted longitudinal lock-up is much more likely. Unstable footrests inevitably produce lateral lock-up which can also be followed by longitudinal lock-up.

#### High Inertia loads without pedals or footrests

Even without the effect of pedals and footrests, high rates of intrusion can still produce high inertia and quasi-static loads following longitudinal ankle lock-up.

Figure 9 shows the lower leg results from a passenger in a front fixed barrier crash test.

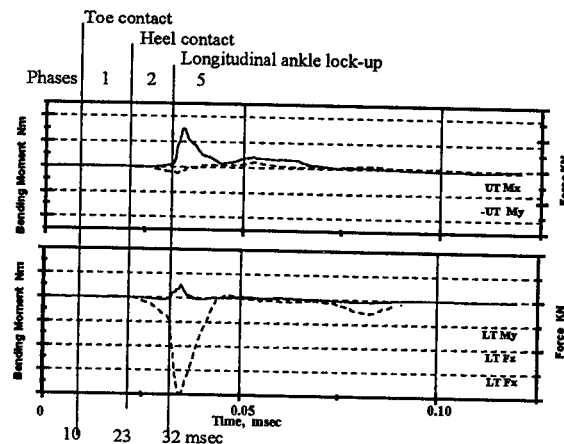


Figure 9 Lower leg test data - High inertia loads, passenger side

With the feet located in very close proximity to the footwell, toe contact occurs at 10 ms, with negligible effect on forces or bending moments as the toe slides up the footwell. Heel contact occurs at 23 ms producing a gradual rise in axial loads and upper tibia bending moments. However, with the onset of dynamic intrusion, longitudinal ankle lock-up occurs rapidly, at 32 ms, producing instantaneous rises in both lower tibia Fz and My with both upper and lower tibia index peaking at 34 ms. The ankle lock-up has occurred so early in the test that it has affected both the femur compressive load and pelvis acceleration as the pelvis to vehicle relative velocity is still significant.

This example shows again that it is not only the magnitude of intrusion that is the significant factor on lower leg loads but also the timing. High inertia and quasi-static loads are produced if a high rate of intrusion occurs while the foot is in direct contact with the footwell.

Analysis of lower leg kinematics and loading mechanisms has been conducted on the majority of lower leg data in the baseline crash test database. Initial evaluation indicates that the smaller footwells, steeper tibia angles and increased intrusion associated with small vehicles tends to compress the kinematic phases decreasing the time to ankle lock-up with the probability of higher quasi-static loads. Increased footwell areas and shallower tibia angles delay the time to initial toe and heel impact increasing both axial and

rotational inertia loads but have a lower probability of longitudinal ankle lock-up.

Timing of intrusion also has a significant effect on lower leg loads. If this occurs during initial heel impact or longitudinal lock-up the inertial or quasi-static loads generated are significantly higher. Therefore the highest rate of intrusion should occur either prior to heel impact or during Phase 3 (ankle rotation) minimising the effect on lower leg loads.

## CONCLUSIONS

Application of increased levels of instrumentation to both the Hybrid III lower leg and vehicle footwell has lead to better understanding of lower leg kinematics and loading mechanisms. Five main lower leg kinematics Phases have been proposed for which the loading mechanisms have been evaluated. A programme of HyGe sled tests have been used to validate these kinematic phases and to link these directly to the loading mechanisms. The 5 main kinematic phases are:

- Toe contact
- Heel contact
- Ankle Rotation
- Lateral ankle lock-up
- Longitudinal Ankle Lock-up

The kinematic analysis technique has been applied to the lower leg data in the LLIMP project baseline crash test database and several different types of lower leg kinematics and lower leg loading mechanisms have been evaluated.

Smaller footwells with higher levels of intrusion, tend to compress the kinematic phases causing longitudinal lock-up to occur earlier, with the probability of higher quasi-static loads. However, larger footwell heel contact is often delayed, producing a higher relative impact velocity and therefore higher inertia loads. Reducing the amount of intrusion obviously decreases the probability of longitudinal ankle lock-up. However changing the time of the highest rate of intrusion away from either the heel contact or ankle lock-up reduces lower leg quasi-static loads.

Pedal and footrest instability cause lateral ankle lock-up which then lead to higher quasi-static loads in longitudinal lock-up. Stable footrests reduce the probability of lateral lock-up and therefore injury criteria.

These conclusions are subject to limits of biofidelity of the lower leg of the Hybrid III dummy, and are therefore potentially useful in evaluating alternative improved dummy designs.

# PARAMETRIC STUDY ON THE EFFECT OF THE FOOTWELL GEOMETRY, DYNAMIC INTRUSION AND OCCUPANT LOCATION ON HYBRID III LOWER LEG INJURY CRITERIA

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## ABSTRACT

Inclusion of lower leg injury criteria in the new European Frontal Impact Legislation has meant that lower leg loads for front seat occupants and footwell deformation have to be considered as part of the vehicle design process at the concept stage.

The Hybrid III dummy with instrumented lower legs is the tool selected for measuring the lower leg injury criteria and it is essential to have a full understanding of the lower leg interaction, with the deforming footwell, control pedals and dashboard, in order to determine how these effect leg kinematics and loading mechanisms.

The LLIMP (Lower Leg Injury and Methods of Prevention) Vehicle Design project is a collaborative research project undertaken by MIRA and sponsored by Rover Group, Ford Motor Company and Jaguar Cars. Its aim is to gain an understanding of the effect which car design has on lower leg kinematics and loading mechanisms. As part of this project a finite element lower leg model has been developed and fully correlated to crash and sled tests. The effect of over 30 different parameters which affect lower leg kinematics and loads have been studied, and their effect on lower leg loading will be evaluated later in the project using the finite element lower leg model. These parameters take account of vehicle structure, occupant kinematics and footwell geometry. The results of the parametric study have been collated to produce a set of lower leg design guidelines, to assist in vehicle structure and

restraint system design and as part of the vehicle development cycle.

The paper presents the formulation of the parameters, and how different parameters effect lower leg kinematics and injury criteria.

## INTRODUCTION

With the increasing awareness over disabling lower leg injuries, reflected in the introduction of lower leg injury criteria in the new European Frontal Impact Protection, Directive 96/79/EC, automobile manufacturers are now focusing considerable attention on footwell design. The Lower Leg Injury and Methods of Prevention (LLIMP) Vehicle Design Project (Ref 1) is investigating lower leg kinematics and loading mechanisms with a view to improving vehicle structural and footwell design. The Vehicle Design Project is an industrial collaborative research project sponsored by Rover Group, Ford Motor Company and Jaguar Cars with the research managed by the Motor Industry Research Association (MIRA).

The objective of the initial phase of the project is to evaluate the sensitivity of the current instrumented Hybrid III lower leg to the factors which effect lower leg kinematics and to collate these to produce a set of guidelines for footwell, pedal/footrest and restraint system design. In order to achieve this objective, lower leg kinematics and loading mechanisms were investigated to determine how different footwell environments affect loads and injury criteria (Ref 1). The project has identified five main

phases in kinematics of the lower leg, each having a characteristic loading mechanism. A finite element computer model of the Hybrid III lower leg has been developed (Ref 2), to be used in evaluating the effect of over 30 different parameters on the lower leg kinematics, loading and injury criteria.

## CHARACTERISATION OF LOWER LEG KINEMATICS

The lower leg loads are generated by a complex interaction between the feet and the footwell, caused by the relative motion of the occupant's legs (controlled by the restraint system) and the footwell surfaces (controlled by the deformation of the front bulkhead). Crandall (Ref3), Sakurai (Ref4) and Zubry (Ref 5) all show the importance of the timing and magnitude of the initial footwell acceleration on impact with the foot, termed 'inertial slap'. The rapid acceleration of the foot and tibia on impact with the footwell, produces a high inertial axial force in the tibia, which as it moves rearwards with angular acceleration produces high bending moments in the upper tibia. Zubry (Ref 5) and Kruger (Ref 6) and many others consider the effect of total footwell intrusion and deformation. These usually produce high axial loads and lower tibia bending moments, generated as the ankle reaches the end of its travel or locks up. Further compressive forces and bending moments are generated as a result of lower leg entrapment. They also comment on the importance of the initial feet position relative to the footwell (on or off pedals and footrests) on lower leg loads.

In the initial phase of the LLIMP project (Ref 1) lower leg load data, from a database of both offset deformable and fixed barrier frontal crash tests were analysed, from which 5 main phases of lower leg kinematics have been proposed. These are shown in Figure 1.

In analysing the lower leg data from the crash test database the existence and duration of each phase and magnitude of the loads within the phases vary dramatically dependent on vehicle structure, leg location and crash test scenario. In vehicles with high intrusion the

phases tend to be compressed with high lower tibia bending moments following longitudinal ankle lock-up. Low intrusion vehicles may have lower probability of ankle lock-up but high upper tibia bending moment and lower tibia axial loads from heel impact with the footwell. As lower leg kinematics are intrinsically linked to loading mechanisms and magnitudes, these also must be considered in evaluating the effect on footwell footrest and pedal design.

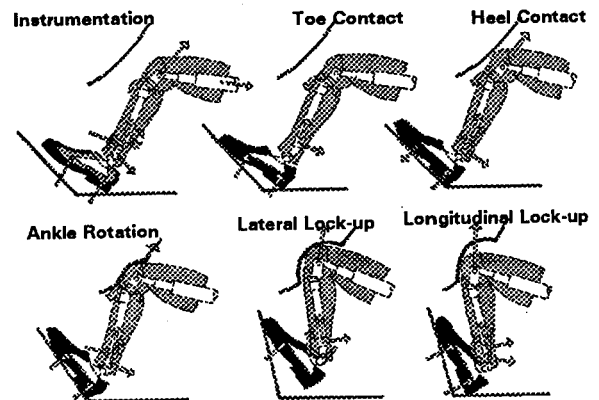


Figure 1 Lower Leg Kinematic Phases

## PARAMETRIC STUDY MODEL CONSTRUCTION

To undertake the parametric study a rigid body finite element (FE) model of the Hybrid III with a validated lower extremity was placed inside a simplified model of a vehicle cabin. From the LLIMP Vehicle Design Project baseline crash data (Ref1) it was possible to identify most of the areas where the greatest detail should be applied in the FE model. The lower leg and occupant model has already been presented (Ref 2) which has provided a comprehensive review of the level of detail needed in modelling the lower extremity. In the current part of the study attention has been concentrated on the modelling of the vehicle cabin.

The aim of the finite element model is to provide a simplified environment to investigate the sensitivities of the lower extremity, to the factors effecting their kinematics and loads. To achieve this it was necessary to understand the motions of both the occupant and the left and right side of the footwell. It is proposed that



the model will be developed to allow facia intrusion to be accurately simulated. However, at this time, the level of modelling detail required for this has not yet been established.

### DUMMY AND LOWER LEG MODEL DEVELOPMENT

Probably the greatest area of importance in the modelling of the dummy is ensuring the accurate representation of it's anthropometry. But, due to the analysis being concentrated on the effects of the lower extremities, it was not necessary for the upper areas of the model to be constructed to the same level of detail. In order for the general kinematics of the dummy to be achieved, it is only necessary for the upper body segments of the dummy to be of the correct size and mass distribution with accurate centres of mass and moments of inertia. The joints of the upper dummy are greatly simplified using the available LS-Dyna3D joint definitions. For the most part, the upper segments were modelled using rigid ellipsoidal representation for the abdomen, upper torso and upper limbs (see Figure 2).

The lower extremity was modelled using accurate geometry giving the body segments' accurate mass distribution, moments of inertia and centres of gravity.

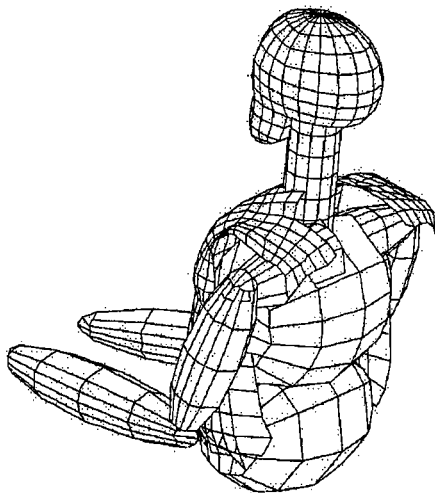


Figure 2 : Model of the upper part of the occupant

The dummy's skeletal structure was modelled as a rigid structure with arrangements of springs and dampers joining the limbs at the locations of the current load-cells (see Figure 3). The load development at these load-cells will be higher than in a real Hybrid III leg since by nature the model lacks compliance in the rigid skeletal structure. As a result, all the forces are transmitted directly to the load-cells and joints. Our experience in the use of this model shows that in most instances the output of these load-cells can be scaled to compensate for the non-compliance. The associated joints are modelled using pre-defined LS-Dyna3D joint models. The ankle, knee and hip joint stiffness characteristics are modelled using non-linear torsional springs and dampers.

The flesh of the lower extremities and the feet were modelled using correlated foam materials, each of which was geometrically accurate. The advantage of accurate geometric representation was an improvement in contact interaction with the vehicle cabin environment.

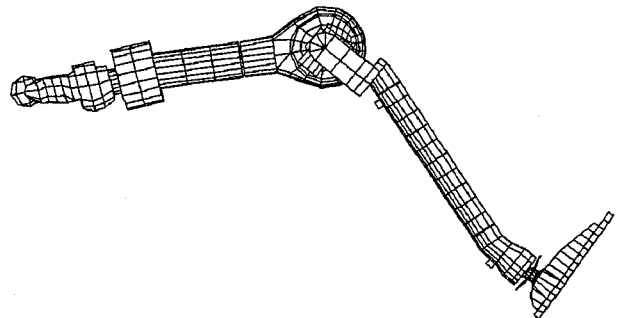


Figure 3 : Model of Hybrid III Leg Structure

Due to the complexity of both the ankle joint and the tibia load-cells, detailed consideration has been given to the method in which these components should be modelled.

## VEHICLE CABIN MODEL DEVELOPMENT

In the LLIMP programme two levels of FE cabin model were developed. The first was an arbitrary cabin with common footwell angles derived from a series of sled tests used in the validation of the FE lower extremity model (see Figure 4). This was used as a guiding tool for determining the level of detail required for a generic baseline cabin model. The early stages of the parametric study required a series of analysis runs to be undertaken with a series of arbitrary intrusion profiles derived from the ranges seen in the baseline crash tests. Each run was used to vary what are believed to be the main parameters that affect the loading mechanisms of the lower extremity. The aim of this was to verify the general behaviour of the lower extremity from the interaction and driven reaction of an intruding cabin structure.

The second level of model was then defined with very simplified interaction requirements, whilst still being able to provide accurate interaction and driven reaction characteristics with the occupant foot and lower leg. The cabin geometry was based on a C-class vehicle (mid sized). This was derived from data provided by Ford, Rover and Jaguar, along with their input on occupant positioning.

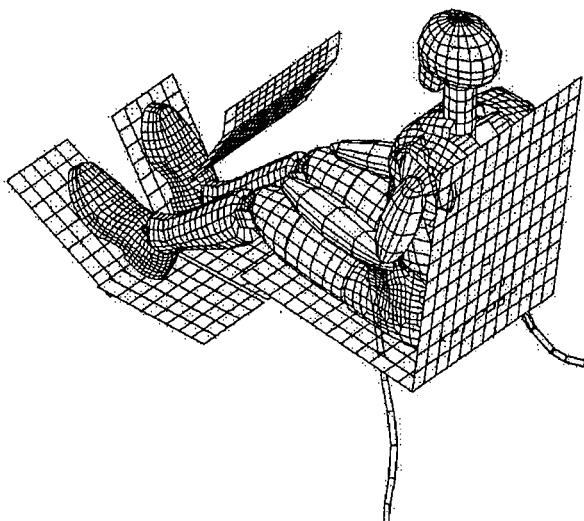


Figure 4: Model of occupant in cabin

The simplified cabin model makes it possible to reduce the number of input variables during the interaction between the occupant and cabin. In particular, by treating the left and right side of the cabin in front of the occupant as separate, it became very easy to control the reaction effects of the occupant to structure. Both levels of cabin model were built around this philosophy.

Using this approach it was possible to define facia stiffness characteristics for each leg impact, and well defined intrusion characteristics for the footwell region. For simplicity, the facia was geometrically defined for the mid-sized vehicle but was treated as a rigid but moveable part in car-line only. This allowed for an effective means of controlling the knee interaction stiffness characteristics through the use of non-linear springs.

The cabin floor and adjoining sides were treated as a single rigid immovable part. Both the footrest and the right side of the footwell were then treated as movable rigid parts that were geometrically accurate. Prescribed translations and rotations were then applied to these parts to mimic the effect of footwell intrusion relative to the occupant.

A typical accelerator pedal was modelled to represent the average shape from the vehicle platforms in the baseline crash tests. This was mounted relative to a rigid movable bulkhead. The prescribed motion of the bulkhead was defined from analysis of the motions experienced in general from the baseline crash data. To represent the reaction load of the pedal on the foot during the impact event, a rotation spring was defined about the pedal pivot pin.

For the current programme of work, the positioning of the right foot is confined to the area of the accelerator pedal. Because of this, it was assumed that any lower extremity contact with the steering column shrouding would have a negligible effect on the loading of the lower leg. Therefore, it was not necessary to incorporate a steering column into the model.

To overcome the need to accurately represent the restraint system, as only the lower extremity injuries were being studied, a prescribed excursion of the pelvis was defined. This method allowed the tight control of the

variables applied to the occupant and the relative cabin intrusion for the parametric study.

## **LOWER LEG PARAMETRIC STUDY**

### **Methodology**

Initial experience within the LLIMP project has shown that the optimum method for reducing lower leg loads to a predetermined level is by using a combination of different parameters rather than one alone. For example to reduce the probability of longitudinal ankle lock-up occurring, rather than just reducing footwell intrusion, with large modifications to vehicle structure, it can be better achieved by combining the effects of reduced pelvis forward motion (seat and restraint system), foot initial position (increasing the foot/tibia angle) and reducing footwell rotation. To enable this methodology to be successfully applied to vehicle design the sensitivity of the Hybrid III lower leg must be evaluated both in terms of kinematics and loads for all parameters. From this the optimum parameters, at both the vehicle concept and development stages, can be selected, for achieving the best solution for least vehicle modification.

In an appraisal, over 30 different parameters were judged to have a significant effect on lower leg kinematics and loading mechanisms. To conduct a full parametric study evaluating the sensitivity of each parameter with its interaction with other parameters would be extremely difficult and time consuming, even using the F.E. lower leg and cabin model. However two factors can be used which significantly simplify the problem.

Firstly, from the analysis of lower leg kinematics two main loading mechanisms have been identified: inertial loading, which predominantly occurs in Phases 1 and 2, and quasi-static loading in Phases 4 and 5. Only parameters which affect each specific loading mechanism need be evaluated in combination.

Secondly, most passenger vehicles are designed around a standard sized occupant (nominally 50<sup>th</sup> percentile male), with seat and steering

wheel adjustment to accommodate the variance in the population. Therefore components such as control pedals, footrests and dashboard are all located within a relatively standard envelope for most vehicles. A baseline cabin model was formulated whose component locations were based on the median locations as measured from a number of different sized passenger cars. As most vehicles component locations will not be significantly different to the median cabin model the problem of combining the effect of different location parameters was significantly reduced. Obviously the effect of the different seating positions in sports cars or sport/utility vehicles would be treated as special cases.

The parametric study commenced by assessing the sensitivity of each parameter individually. The effect of combining parameters was then evaluated where parameters were strongly linked. An example of this is for the specific loading mechanism of ankle lock-up, where footwell translation, footwell rotation and pelvis forward motion are intrinsically linked.

In the parametric study all the parameters which potentially affect lower leg kinematics and loading have been divided into three main categories.

- Vehicle structure
- Occupant kinematics
- Footwell geometry

Table 1 shows the main parameters for each of the above categories. Initial results of the parametric study are given below, whilst more in-depth computer simulation is on going for each of the parameters.

### **Structural Characteristics**

The structural performance of the vehicle has a significant affect on Hybrid III lower leg kinematics and subsequent loading. The intrusion profile of the footwell is dependent upon the vehicle structure's load paths and the interaction of rigid components (engine, gearbox, etc) with the footwell. The intrusion profile of the footwell can be considered a

combination of translational and rotational motions, see Figure 5.

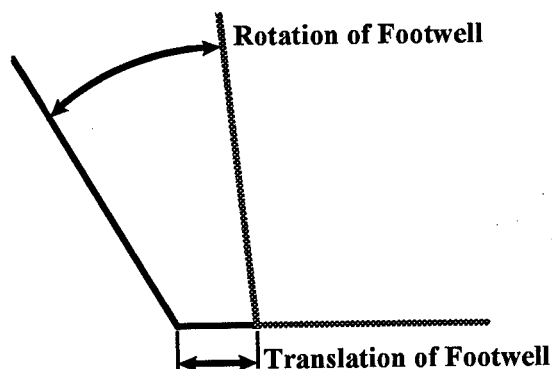


Figure 5: Footwell Motion

Analysis of vehicle crashes from the LLIMP crash test database, shows maximum footwell translations of 250mm, and rotations of  $25^\circ$ . With maximum pelvis forward trajectory of 300mm, this produces over 600mm relative motion at the foot.

Quasi-static loading is produced when the ankle rotates and reaches its end stop. Further rotation produces a bending moment in the tibia which increases the resulting tibia index. In a typical vehicle this occurs after an ankle rotation of approximately  $45^\circ$ . At the same time a pelvis forward motion or footwell translation of 200mm represents an ankle rotation of approximately  $24^\circ$ . It is clear that a combination of intrusion and pelvis forward motion increases the likelihood of ankle lock-up.

Ankle lock-up and subsequent loading is sensitive to both translation and rotation of the footwell.

Totally eliminating intrusion into the passenger compartment during the European frontal crash test is extremely challenging with current vehicle design. However load path management should aim to control the levels of intrusion and in particular minimise footwell rotation. This will greatly reduce the risk of ankle lock-up and the subsequent increase in tibia loading.

Figure 6 shows the reduction in tibia bending moment that can be achieved with a 50% reduction in footwell rotation. This delay and reduction in quasi-static load is due to the reduced footwell rotation delaying the onset of ankle lock-up and subsequent tibia bending moment.

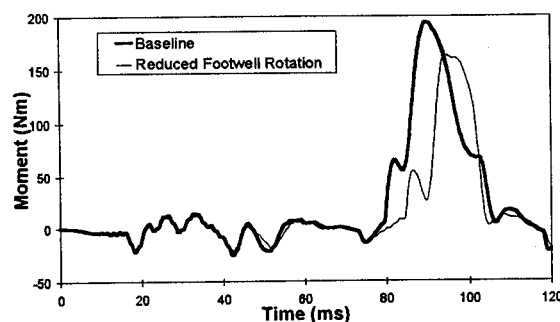


Figure 6: Effect of Reduced Footwell Rotations on Bending Moment

The generic baseline model used 100mm translation,  $20^\circ$  rotation and 230mm pelvis forward motion.

### Occupant Kinematics

The motion of the pelvis had a significant effect on the level of ankle rotation and subsequent tibia loading. The greater the pelvis forward motion the greater the level of ankle rotation. This results in increased quasi-static lower leg loading.

This pelvis forward motion is controlled by the seat, restraint system and knee contact with the instrument panel. Effective management of these systems can reduce the level of pelvis forward motion. However it cannot be entirely eliminated as it is necessary in reducing occupant injuries due to vehicle deceleration.

Figure 7 shows the reduction in tibia bending moment that can be achieved with a 25% reduction in pelvis forward motion.

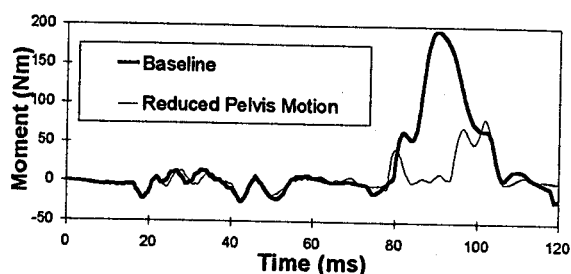


Figure 7: Effect of Reduced Pelvis Motions on Bending Moment

Figure 8 shows the reduction in tibia compressive load,  $F_z$  during the quasi static loading phase which runs from approximately 75 to 105ms. However the inertial loads 20 to 60 ms remain unaffected.

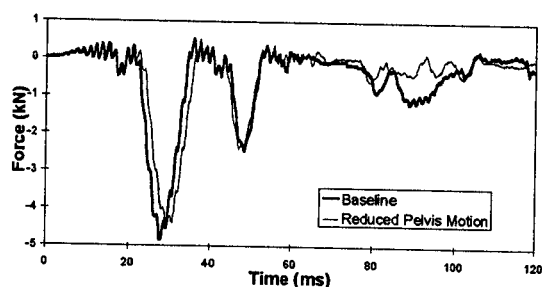


Figure 8: Effect of Reduced Pelvis Motions on Compressive Load

The lower leg loads are very sensitive to the magnitude and timing of pelvis forward motion.

If tibia loads are to be minimised it is important that the intrusion, ankle lock-up and pelvis forward motion should be controlled. If ankle lock-up can be delayed the subsequent tibia loads are reduced.

The lower leg kinematics determine the interaction of the knee with the knee bolster. The entrapment of the knee in the bolster has an effect on the three dimensional response of

the lower legs and the axial load that can develop.

### Footwell Geometry

The initial geometry of the footwell has a significant affect on lower leg kinematics and subsequent loading. The angle of the footwell affects the inertial and quasi-static loading on the lower leg.

A shallower footwell angle will result in reduced upper tibia inertia loading. This will increase tibia axial load but the current tibia index is much more sensitive to bending moments. The shallower angle also increases the amount of ankle rotation which is necessary to achieve ankle lock-up. This delays ankle lock-up and therefore reduces subsequent tibia loading. The distance of the footwell from the occupant also affects the tibia loads. The greater the distance the greater the relative velocity of the lower legs and the vehicle structure. This increases the inertia loads that are produced when the feet contact the structure. This distance also determines the degree of ankle rotation before lock-up. This affects the timing of lock-up and subsequent tibia loading.

### Further Studies

Further analysis of the parameters that affect lower leg loading is being conducted.

The stiffness of the footwell determines the load that is transferred though the vehicle structure to the occupant. This has an affect on the lower leg loads during the inertial and quasi-static phases.

The three dimensional response of the Hybrid III lower leg is an important aspect of understanding the loading mechanisms. The geometry and intrusion characteristics of the footrest and pedals determine the stability of foot contact. Instability leads to lateral ankle rotation and subsequent tibia lateral bending moment. This lateral bending moment can be greater than the longitudinal bending moment.

Further parametric studies will determine the contributions that these and other parameters have on lower leg loading.

## CONCLUSIONS

With increasing awareness of lower leg injuries and inclusion of lower leg injury criteria in the new European Frontal Impact Directive, automobile manufacturers are now focusing on footwell, footrest and control pedal design. An objective of the Lower Leg Injuries and Methods of Prevention Vehicle Design Project is to produce a set of footwell design guidelines to assist the vehicle designer in selecting the optimum parameters. Experience has shown that the best method of reducing lower leg loads is by reducing the effect of a number of parameters rather than concentrating on one.

The objective of the parametric study was therefore to evaluate the sensitivity of the HIII lower leg to the effect of changing over 30 parameters for both kinematics and loads. In order to conduct such a large study a Finite Element lower leg model has been developed and validated to both sled and crash test lower leg data.

The parameters have been divided into three main categories:-

- Vehicle Structure
- Occupant Kinematics
- Footwell Geometry

Analysis of the main parameters have shown the relationship between both footwell rearward and pelvis forward motion result in reducing the tibia / foot angle and therefore increase the probability of ankle lock-up occurring. Reducing footwell rotation delayed the onset of ankle lock-up and reduced tibia bending moments, while reducing pelvis forward motion reduced both axial loads and bending moments. Increasing the initial foot angle also delayed ankle lock-up and subsequent tibia loading.

The lower leg with the associated cabin model now provides a powerful tool for footwell

design as the complex dynamic interaction between the lower leg and footwell can be simulated. The parametric study has identified the critical parameters, with their loading mechanisms, which can be used to optimise footwell design.

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3. J R Crandall, C R Bass, G S Klopp, W D Pikey - "Sled Tests with Toepan Intrusions Using Post-mortem, Human Surrogates and the Hybrid III Dummy"
4. M Sakurai - "An Analysis of Injury Mechanisms for Ankle/Foot Region in Frontal Offset Collisions" - 4<sup>th</sup> Stapp Car Crash Conference, 1996, SAE Paper No 962429
5. D S Zuby, C H Farmer - "Lower Extremity Loads in Offset Frontal Crashes" - 15<sup>th</sup> International Conference on the Enhanced Safety of Vehicles 1996, Paper No 96-S3-O-04
6. H Kruger, G Heuser, B Kraemer, A Schmitz - "Foot Load and Footwell Intrusion in an Offset Front Crash" - 14<sup>th</sup> International Conference on the Enhanced Safety of Vehicles, 1994. Paper No 94-S4-O-03

Vehicle Structure Dynamic Intrusion	Rotation start	ms
	Rotation initial acceleration	rad <sup>-2</sup>
	Rotation rate	rad <sup>-1</sup>
	Rotation total amount	rad
	Translation start	ms
	Translation initial acceleration	ms <sup>-2</sup>
	Translation rate	ms <sup>-1</sup>
	Translation total amount	m
	Pedal lateral motion	m
Occupant Kinematics	Footrest lateral motion	m
	Pelvis forward motion total amount	m
	Pelvis forward motion rate	ms <sup>-1</sup>
	Seat base angle	deg
	Seat anti-submarine characteristics	kNm <sup>-1</sup>
	Initial foot/tibia angle	deg
	Heel longitudinal location	m
Footwell Geometry	Heel lateral location	m
	Toeboard angle	deg
	Footwell-toeboard curvature	degm <sup>-1</sup>
	Pedal upper pivot location	m
	Footrest/pedal longitudinal location	m
	Footrest/pedal lateral location	m
	Footrest/pedal width	m
	Pedal distance of travel	m
	Pedal stiffness characteristics	kNm <sup>-1</sup>
	Footrest/pedal surface friction	N
	Footrest angle	deg
	Footwell stiffness characteristics	kNm <sup>-1</sup>
	Carpet/underlay thickness	m
	Carpet/underlay characteristics	kNm <sup>-1</sup>
	Carpet friction	N
	Lower dashboard longitudinal location	m
	Lower dashboard angle	deg
	Lower dashboard characteristics	kNm <sup>-1</sup>

Table 1 Footwell Design Parameters

# AN INFLATABLE CARPET TO REDUCE THE LOADING OF THE LOWER EXTREMITIES - EVALUATION BY A NEW SLED TEST METHOD WITH TOEPAN INTRUSION

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Paper Number 98-S1-P-18

## ABSTRACT

For occupants protected by seat belts, air bags, or both, the most frequently injured body region in frontal crashes is the lower extremities. These injuries are usually not life threatening, but they are often associated with long term impairment. The injury mechanisms are not yet fully understood. However, high local accelerations in the footwell area and the location of the feet probably play an important role in the causation of the injuries. A reduction of the footwell intrusion by structural reinforcements of the car body may therefore not be sufficient to reduce injuries. Other counter-measures are also needed.

This paper describes a new dynamic sled test method with an instrumented Hybrid III dummy in a car body, in which the toepan intrusion is simulated mechanically. The acceleration-time history of the toepan and its displacement can be varied. Toepan accelerations/intrusions as in severe frontal off-set collisions have been simulated. Two foot positions, against the toepan or at a certain distance (as if the foot was on a pedal), were evaluated.

The effect of an inflatable device, called the Inflatable Carpet (InCa), under the floor carpet in the footwell area is evaluated by this method. The Inflatable Carpet lifts the feet away a certain distance from the floor/toepan, before they are subjected to acceleration and intrusion by the toepan.

The study has shown that the acceleration of the toepan, the position of the feet relative to the toepan, and the use of the Inflatable Carpet, all significantly influenced the load on the foot and the lower leg. The use of the Inflatable Carpet reduced the foot acceleration by up to 65 % and the tibia force by up to 50 %. The tibia index was reduced by 30 to 60 %. The Inflatable Carpet therefore seems to be able to significantly reduce the risk of receiving an injury to the foot/ankle and lower leg in collisions, where violent footwell intrusion occurs.

## INTRODUCTION

The lower extremities are among the most frequently injured body regions in car collisions regardless of restraint (Crandall and Martin, 1997a). About 70 % of these injuries are sustained in frontal collisions (Pattimore et al., 1991; Parenteau et al., 1995; Crandall and Martin, 1997a). Pattimore et al. (1991) found, using U.K. crash data (U.K. Cooperative Crash Injury Study), that 37 % of injured car occupants had sustained injuries to the lower extremities. The seat belt use was high, at about 85 %. Crandall and Martin (1997a) found, using U.S. crash data (NASS-CDS), that in frontal collisions almost 40 % of the AIS 2+ injuries to front seat occupants, restrained by airbags and belts, were to the lower extremities. 60 % of these injuries were below the knee; 20 % to the lower leg and 40 % to the foot/ankle.

Ankle injuries account for the majority of AIS 2+ injuries in Volvo's data base (Forsell et al., 1996). Malleolus fractures in the distal ends of tibia and fibula and "pilon" fractures of the talus were typical. Crandall et al. (1995) found that ankle and calcaneus (heel bone) fractures are the most frequent injuries, evident at all levels of footwell intrusion.

Although the injuries to lower extremities are rarely life threatening, they can lead to long term disability and impairment (Pattimore et al., 1991; Frampton et al., 1995). Parenteau (1996) found in a Swedish study that 48 % of AIS 2+ foot/ankle injuries were estimated to have residual impairment. A German study by Zeidler et al. (1989) found that the rate of permanent impairment for heel fractures was as high as 72 %, and for open tibia/fibula fractures 43 %.

About 50 % of AIS 2+ lower extremity injuries sustained in frontal crashes occur in collisions with  $\Delta v$  ranging from 25-50 km/h. Only 20 % occur in extremely high severity crashes, where  $\Delta v$  exceeds 70 km/h (Crandall and Martin, 1997a). However, the risk of injury to the lower extremities increase, when either  $\Delta v$  or the magnitude of intrusion increases (Thomas et al., 1995; Fildes et al., 1995; Crandall and Martin, 1997a). Substantial intrusion of the



footwell is not a necessary condition. 71 % of all and 61 % of AIS 2+ below-knee injuries sustained by front seat occupants in head-on crashes occurred with less than 30 mm of footwell intrusion according to a study by Crandall et al. (1995). This suggests that for these injuries there may be more sensitive crash factors other than the level of intrusion, e.g. the rate or the acceleration of intrusion.

Kuppa and Sieveka (1995) found in a series of full-scale tests that the axial loads measured just above the ankles in the dummies were highly correlated with the peak acceleration of the floor/toeapan or the brake pedal. However, these axial loads did not correlate well with the amount of floor/toeapan or brake pedal intrusion. This suggests that the axial loads through the feet of the dummy are caused by the dynamic motion of the surface on which the feet rest. The tests showed that high acceleration-short duration floor/toeapan pulses led to low levels of intrusion but resulted in high axial loads through the dummy feet. Conversely, the data from the tests showed that low acceleration-long duration floor/toeapan pulses led to high levels of intrusion but resulted in low axial loads through the dummy feet.

About half of all drivers, who sustain lower extremity injuries, are braking at the time of collision. Several studies have shown that the increased risk of below-knee injuries for drivers is primarily the result of interaction with pedal controls (Morgan et al., 1991; Pattimore et al., 1991). When the foot is on a pedal and the heel is off the toeapan, a velocity differential develops between the foot and toeapan that makes the foot vulnerable to impact injury (Crandall and Martin, 1997a). Crandall et al. (1995) also found in a series of crash tests that there was a tendency for greater loads in the right leg compared to the left. The right foot of the dummy was placed on the accelerator pedal, while the left foot rested on the toeapan. Forsell et al. (1996) found by mathematical simulations that the foot to toeapan impact speed affected the tibia force. An increased distance between the foot and toeapan led to a higher foot impact speed.

The question is then raised. Can an energy absorbing padding material placed over the floor/toeapan reduce the high forces being transmitted to the occupant's feet, when there is a violent footwell intrusion? Kuppa and Sieveka (1995), and Forsell et al. (1996) found by mathematical simulations, and the latter also by tests, that padding was efficient in reducing the axial load in the dummy's lower leg. A thickness of about 30 mm reduced the tibia force by about one third.

This study focuses on an alternative to padding in the footwell area, an inflatable device called the Inflatable Carpet to protect the feet/ankles and the lower legs of the front seat occupants. The thickness of the Inflatable Carpet

is about 70 mm, when it is inflated in a frontal collision. Normally the (uninflated) thickness is less than 10 mm.

The aim of the present study was to investigate the effect of the acceleration of the toeapan on the loading of the foot and lower leg for two foot positions, against the toeapan or at a certain distance (as if the foot was on a pedal), by means of a new sled test method. Furthermore, the study aimed to investigate the effect of the Inflatable Carpet.

## METHOD

A sled test method was developed, where a translational toeapan intrusion could be simulated mechanically. The acceleration of the toeapan as well as the amount of intrusion could be varied. A translational toeapan intrusion was chosen based on results of mathematical simulations of a 56 km/h, 50 % off-set crash with a Ford Taurus against a rigid barrier (Pipkorn, 1998). In these simulations, the toeapan intrusion was found to be mainly translational. This type of toeapan simulation has also been performed by others (Bass et al., 1997). The tests were made with two different foot positions, against the toeapan or at a certain distance, with and without the Inflatable Carpet. The acceleration of the dummy's right foot and the axial force of the right lower leg were measured for all test configurations. The crash pulse of the car body on the sled was achieved by a steel bar bending brake system and the desired acceleration pulse of the toeapan was achieved by crushing of a honey comb block mounted in front of the brake.

## Vehicle rig

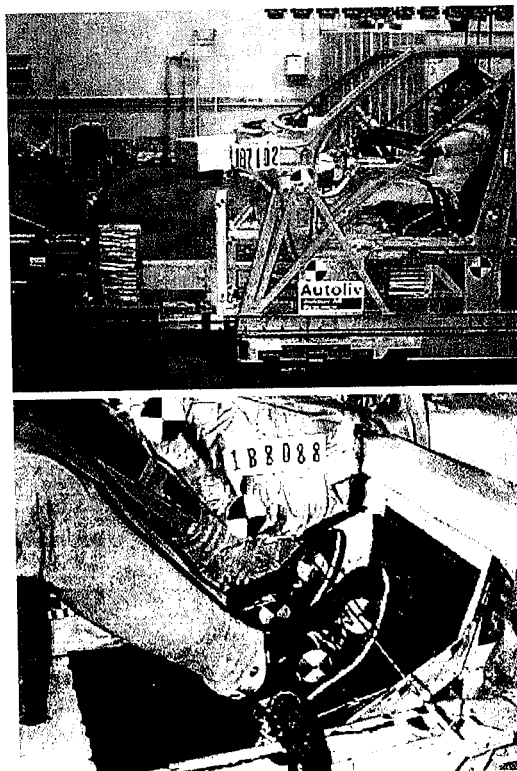
A body in white (BIW) of a large-size car was placed on the crash sled of Autoliv Research (Figure 1). The tests were performed for the driver's side. A Hybrid III dummy with instrumented lower leg (45° ankle joint with soft stops) was placed in a reinforced standard car seat. The steering wheel attachment was also reinforced so as not to deform in the tests. The knee bolster had the dimension of the original car but was made of steel covered with a 25 mm thick padding (Ethafom 400) which was replaced, when there was a permanent crush. The outside of the knee bolster was covered with a 1 mm polyethylene sheet. A 3-point static seat belt with high webbing elongation (18 % at 10 kN) was used. The belt was replaced before each test and pre-tensioned to about 100 N. These measures were taken in order to achieve the best level of repeatability for the tests as possible.

## Toeapan intrusion simulation

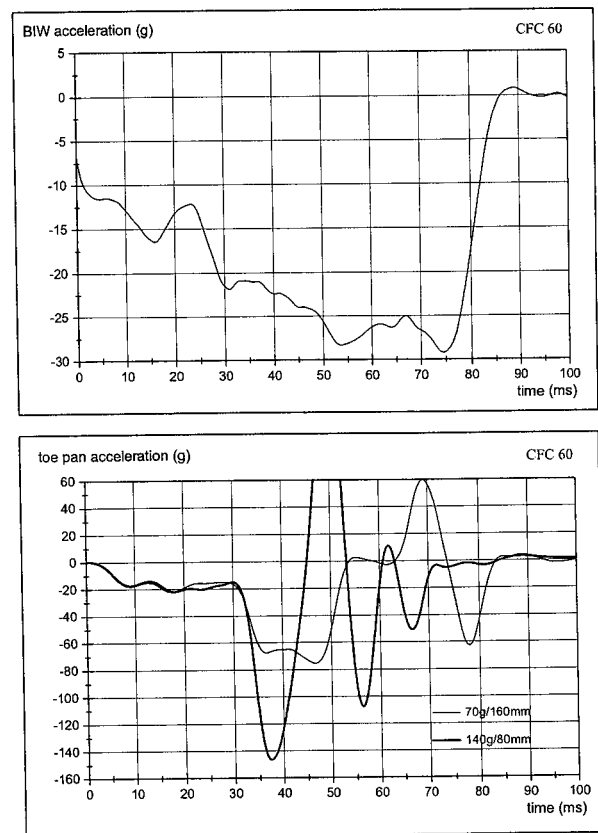
The toeapan, a piece of the fire wall, and the greater part of the floorpan were cut out of the BIW. A new structure

with the same geometry was made of stiff steel plates. This new toe- and floorpan floor was mounted on a separate small sled. The toe- and floorpan sled was equipped with ball bearings running in horizontal guiding rails, which were mounted to the crash sled with the BIW (Figure 1). A honey comb block (Hexcel CRIII-3/8-ACG-.003N) was placed in front of the brake system. By choosing size and position of the honey comb block, the timing and amplitude of the intrusion pulse could be varied. The maximum intrusion of the toe-pan was controlled by a stop, which could be moved within the BIW and fitted with a thin piece of stiff polyurethane padding.

The crash pulse of the BIW was intended to correspond to a 56 km/h off-set rigid barrier test. The tests were performed with two different toe-pan accelerations. A high amplitude acceleration pulse of the toe-pan with small residual (translational) intrusion (140g/80mm), and a low amplitude acceleration pulse with large residual intrusion, (70g/160mm) were used. It was decided to begin the toe-pan intrusion at about 32 ms for both pulses (Figure 2). Two different foot positions were tested.



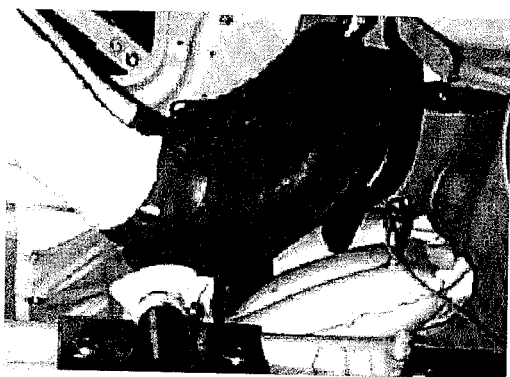
**Figure 1.** The vehicle rig with toe-pan intrusion simulation. (The knee- to knee bolster clearance is about 85 mm).



**Figure 2.** The acceleration pulse of the BIW and the two toe-pan acceleration pulses. BIW  $\Delta v = 56$  km/h.  
**Note.** The feet loose contact with the toe-pan, when the acceleration changes sign. The second acceleration peak is not inducing any foot or lower leg loads.

### Inflatable Carpet (InCa)

The Inflatable Carpet is of the same design as the Inflatable Curtain (Öhlund et al., 1998), about 70 mm thick when inflated and covering an area of about 450 x 350 mm (Figure 3). A hybrid gas generator (Autoflator H2010) was used and inflated the Inflatable Carpet to a pressure of about 150 kPa within 20 ms from triggering. A 3 mm sheet of acetal plastic and the regular carpet were placed on top of the Inflatable Carpet. On the reverse side of the toe-pan section of the acetal sheet, three horizontal load distributing stripes of aluminium, 50 mm wide and 3 mm thick, were attached. The acetal sheet, the aluminium stripes and the regular carpet were glued together. In the tests without the Inflatable Carpet this package was placed directly on the floor- and toe-pan.



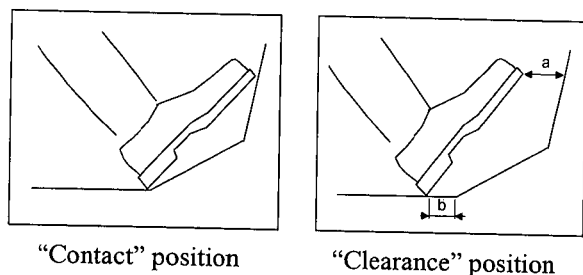
**Figure 3.** The Inflatable Carpet (InCa). The picture shows the Inflatable Carpet only, without plastic sheet and regular carpet.

### Instrumentation

The accelerations of the BIW and the toe- and floorpan sled were measured with accelerometers (Entran EGCS-D1CM-100 and Endevco 7231C-750). The position of the intruding toepan was measured with a string potentiometer (Celesco PT101-25-311-S11D). A standard Hybrid III 50th percentile dummy was used. The right and left upper legs of the dummy were equipped with femur load sensors (Load Indicator). The right leg was equipped with an enhanced lower tibia and with an accelerometer in the foot (Endevco 7264B-2000). The foot accelerometer was placed on the steel plate directly in front of the ankle joint. The internal pressure of the Inflatable Carpet was measured with a pressure transducer (Endevco 8510C-100 M37). On board and over view high speed video cameras were used (Kodak Ektapro RO).

### Foot positions

The tests were performed with two different foot positions (Figure 4 and Table 1). In the first position, the feet were in contact with the toepan and in the second at a small distance away from the toepan. These two positions were chosen so the effect of a clearance to the toepan (simulating a foot on an accelerator or a brake pedal) could be studied.



**Figure 4.** The two foot positions; each tested with and without the Inflatable Carpet.

**Table 1.**

Measures according to Fig. 4 for the two foot positions

Configuration	a (mm)	b (mm)
contact	0	0
clearance	100	50

### Test matrix

The tests were run with the two foot positions according to figure 4, and with the two different toepan pulses, 70 g and 140 g according to figure 2. For each test condition, tests with and without the Inflatable Carpet were run (Table 2).

**Table 2.**

Test matrix

Foot position	Toepan pulse (g)	Residual intrusion (mm)	Inflatable Carpet (Y/N)
Contact	140	80	N
Contact	140	80	Y
Contact	70	160	N
Contact	70	160	Y
Clearance	140	80	N
Clearance	140	80	Y
Clearance	70	160	N
Clearance	70	160	Y

Each test configuration was normally run only once. However, the configuration with the foot position "contact", intrusion of 160 mm and without the Inflatable Carpet was run four times to study the repeatability. (These found variations were then considered to be the same for all evaluated configurations, when testing the statistical significance).

### Injury assessment reference values (IARVs)

- The injury assessment reference value of the foot acceleration is proposed to be 150 g (Zeidler et al., 1996). (As there is no prescriptions for placement of the accelerometer, filter class or duration of the maximum acceleration, this value can only be used as a guideline).
- The tibia force should not exceed 8 kN (EU, 1996).
- The tibia index should not exceed 1.3 at the proximal or distal end of the tibia (EU, 1996).

## RESULTS

The foot acceleration, tibia force and the upper tibia index were all significantly reduced in the tests with the Inflatable Carpet (Figure 5 and Table 3) compared to the tests without. The lower tibia index was reduced in the "clearance" position but was unaffected or even slightly increased in the "contact" position. The results clearly show that the toepan pulse with 140 g acceleration and 80 mm of residual intrusion results in higher foot and lower leg loads than the 70 g toepan pulse with a larger (160 mm) intrusion. The foot acceleration for the higher pulse was doubled, and the tibia force increased 35 to 93 % (without the Inflatable Carpet).

It is also obvious when comparing the results of the tests with the feet in "contact" with those in "clearance" positions, that the pre-crash position of the feet is a very important factor. The foot acceleration was reduced by 33 to 66 % and the tibia force by 22 to 49 %, when the results from tests with the Inflatable Carpet were compared with the tests without the Inflatable Carpet. The upper tibia index was reduced by 30 to 62 %.

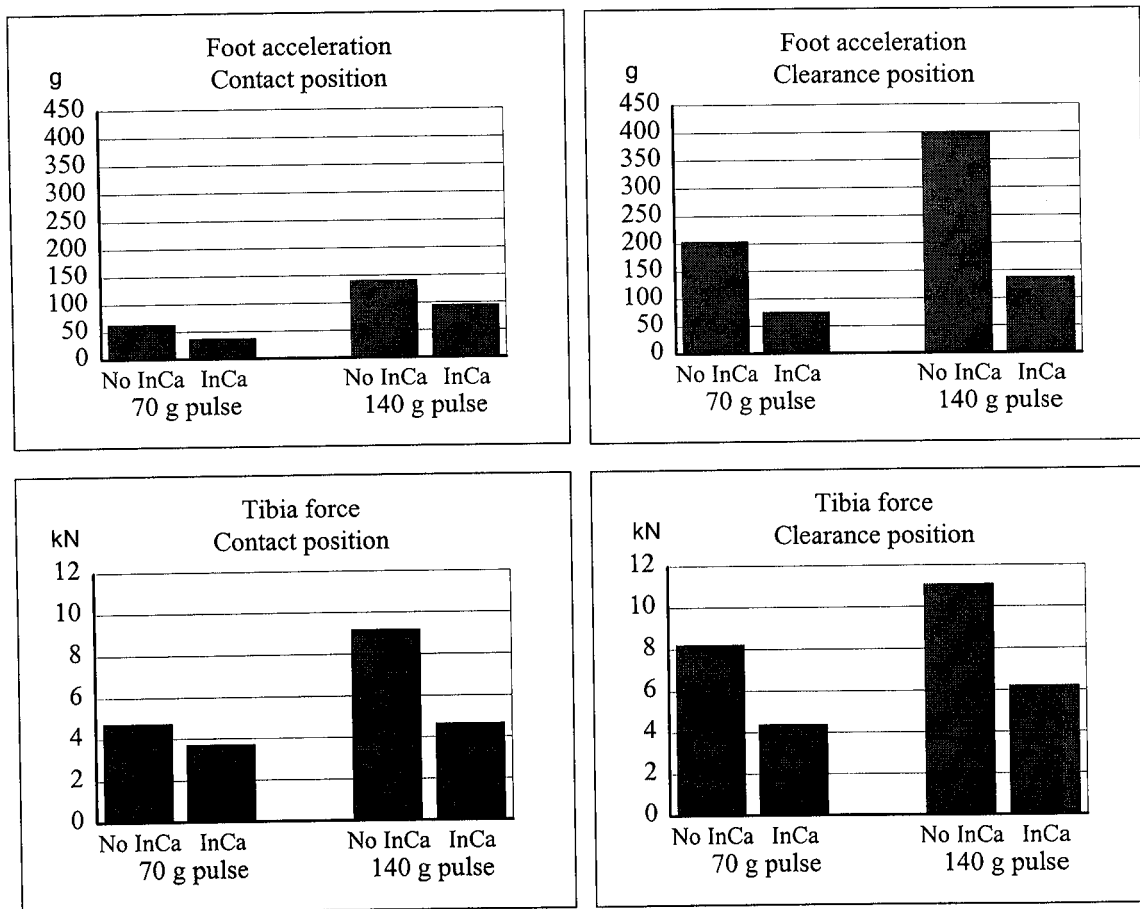


Figure 5. The peak values of the foot acceleration, tibia force and tibia index (lower and upper tibia) for all tests.

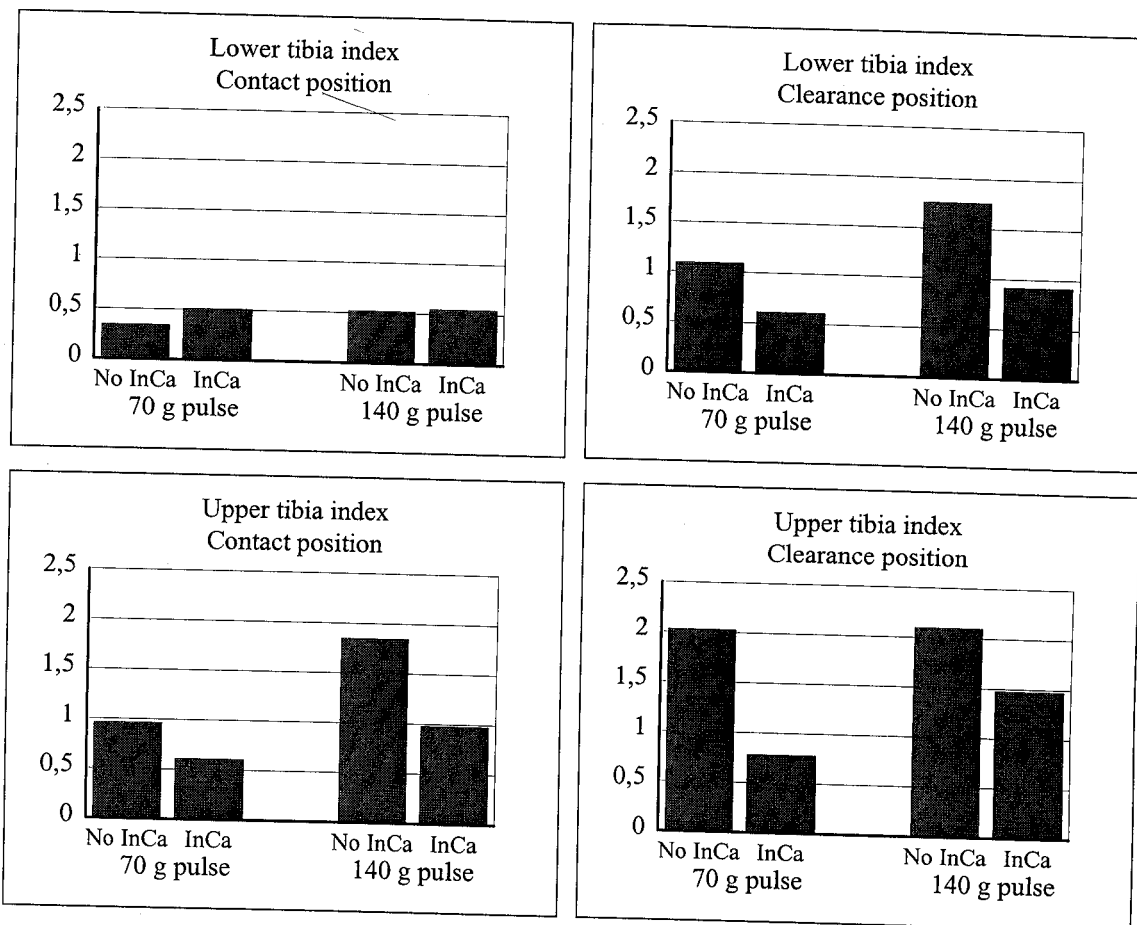


Figure 5. cont. The peak values of the foot acceleration, tibia force and tibia index (lower and upper tibia) for all tests.

**Table 3**  
The peak values of tibia index (lower and upper tibia), tibia force and foot acceleration for all tests.  
The marked values are those which failed to pass the IARVs

Test no	Foot position	Toepan pulse (g)	Intrus. (mm)	InCa (Y/N)	Tibia Index lower tibia	Tibia Index upper tibia	Tibia force cfc600 (kN)	Foot acc cfc600 (g)
76	Contact	140	80	N	0.52	1.85	-9.18	141
77	Contact	140	80	Y	0.55	0.98	-4.65	95
*	Contact	70	160	N	0.35	0.97	-4.75	63
78	Contact	70	160	Y	0.51	0.61	-3.71	37
80**	Clearance	140	80	N	1.76	2.10	-11.1	401
79	Clearance	140	80	Y	0.88	1.43	-6.34	134
90	Clearance	70	160	N	1.09	2.03	-8.23	204
89	Clearance	70	160	Y	0.61	0.78	-4.39	76

\* Mean value, see table 4.

\*\* Foot deformed in test no. 80 (repaired).

**Table 4**  
**Study of the repeatability of one tested configuration**

Study of the repeatability of one tested configuration								
Test no	Foot position	Toe pan pulse (g)	Intrus. (mm)	InCa (Y/N)	Tibia Index lower tibia	Tibia Index upper tibia	Tibia force cfc600 (kN)	Foot acc cfc600 (g)
75	Contact	70	160	N	0.42	0.93	-4.44	60.4
85					0.36	1.10	-5.60	70.7
86					0.31	0.93	-4.55	66.4
87					0.29	0.90	-4.41	55.1
Mean					0.35	0.97	-4.75	63.2
Std. error of the mean (SE)*					+/- 0.025	+/- 0.039	+/- 0.25	+/- 3.0

\*  $SE = SD/\sqrt{n}$ , where SD = std. deviation and n=no. of tests (n=4).

The results of the repeatability study can be found in table 4. Tests (t-test) of statistical significance were done. These showed that the differences in measured peak values between all test configurations with and without the Inflatable Carpet were statistically significant ( $p<0.001-0.05$ ) for upper tibia index, tibia force and foot acceleration. The differences for the lower tibia index were also significant ( $p<0.001-0.01$ ) with exception for test no. 76 compared to test no. 77.

## DISCUSSION

Kuppa and Sieveka (1995) found in a series of full-scale tests that high acceleration-short duration floor/toe pan pulses led to a low level of intrusion but resulted in high axial loads through the dummy feet. Conversely, the data from the tests showed that low acceleration-long duration floor/toe pan pulses led to high levels of intrusion but resulted in low axial loads through the dummy feet. These findings have been taken into consideration in the test method developed for this study. The two acceleration levels of the toe pan, 70 g and 140 g, were chosen based on a recommendation from Crandall (1997b) that the acceleration of the foot in a position against the toe pan should exceed 100 g (a severe test condition). A foot acceleration of 141 g was reached without the Inflatable Carpet in the "contact" position for the 140 g toe pan pulse and 63 g in foot acceleration for the 70 g pulse. The test method thus simulates one toe pan acceleration/intrusion condition that is worse than what Crandall suggested and one that is less severe. The tests confirmed the earlier findings by Kuppa and Sieveka (1995) that the loading of the foot and the lower leg (tibia) can vary considerably between tests with significantly different toe pan acceleration/intrusion levels.

About half of all drivers, who sustain lower extremity injuries, are braking at the time of collision. The leg muscles are therefore tensed. The effect of this pre-impact bracing was investigated by Klopp et al. (1995) in a series of lower

limb impact tests. A harness was placed over the knee and tensed to give a tibia load of about half the body weight. The tests showed that the forces and moments in the lower limb increased significantly due to this simulated pre-impact bracing. This type of simulation should therefore be included in further tests and evaluations of the effect of the Inflatable Carpet.

Several studies have shown that the risk of below-knee injuries for drivers is primarily the result of interaction with pedal controls (Morgan et al., 1991; Pattimore et al., 1997). When the foot is on the pedal and the heel is off the toe pan, a velocity differential develops between the foot and toe pan that makes the foot vulnerable to impact injury (Crandall and Martin, 1997a). The "clearance" position was therefore chosen as well. The results from the tests confirm that the distance between the foot and toe pan has a very strong effect on both the foot acceleration and tibia force. The foot acceleration increased from 63 g in the test with "contact" position to 204 g in the test with "clearance" position for the 70 g toe pan pulse. The tibia force increased from 4.8 kN to 8.2 kN (Figure 5). The results mentioned are from tests without the Inflatable Carpet. In the tests with the 140 g toe pan pulse, the foot acceleration increased from 141 g to 401 g and the tibia force from 9.2 kN to 11.1 kN. The distance between the foot and the toe pan in the tests with the "clearance" foot position developed a velocity difference of about 10 m/s for the 70 g toe pan pulse and 12 m/s for the 140 g pulse. The contact between the foot and the toe pan occurred, when the toe pan still was undergoing acceleration. The loading of the foot and lower leg is thus caused by a combined effect of the toe pan acceleration and the velocity difference between the foot and the toe pan at the time of contact.

In an earlier investigation performed within Autoliv Research, a complete leg of a Hybrid III dummy was used in drop tests against a concrete floor. It was found that the foot acceleration, as well as the tibia force, was almost linearly proportional to the contact velocity with the floor. The highest velocity tested was 6 m/s. This was the first

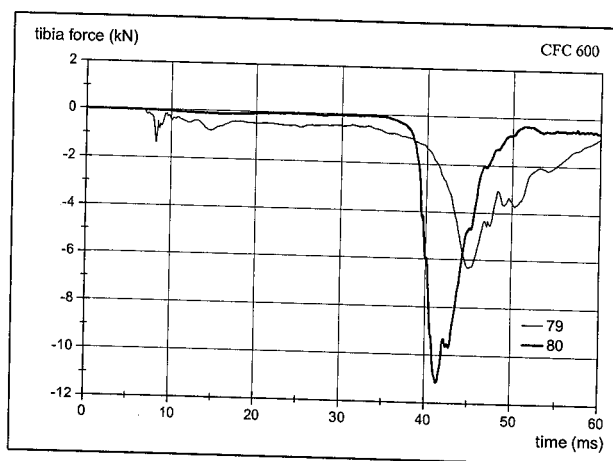
indication from own test results that the contact velocity is a very important factor. The drop tests with the Hybrid III leg also showed the effect of various paddings and of the Inflatable Carpet. An Inflatable Carpet of 70 mm thickness and with a pressure of about 150 kPa (1.5 bar) reduced the foot acceleration and the tibia force by 40 - 60 %. The current study also shows considerable reductions in these loads by the Inflatable Carpet. The largest reductions were found in the tests with the "clearance" position of the foot. The foot acceleration was reduced by about 3/4 by the Inflatable Carpet in tests at both toe pan accelerations levels. The tibia force was reduced by almost 1/2. In the most severe test condition, with the foot in "clearance" position and with the 140 g toe pan pulse, the foot acceleration was reduced by the Inflatable Carpet below the suggested injury assessment reference value (IARV) of 150 g, down to 134 g. Without the Inflatable Carpet, the maximum foot acceleration was much higher, 401 g. The tibia force was also reduced below the IARV of 8 kN, down to 6.3 kN. Without the Inflatable Carpet the maximum value was 11.1 kN. The Inflatable Carpet thus seems to act as a very efficient shock absorber, when there is a violent toe pan intrusion.

The tibia index is an official lower leg criterion in the new European frontal test procedure (EU, 1996). The maximum allowed level is 1.3. The index measured for the upper tibia was higher for all tested configurations than the index for the lower tibia. The highest tibia index, of 2.1, was reached with the 140 g toe pan acceleration, "clearance" foot position, and without the Inflatable Carpet (Figure 5). The upper tibia index was reduced by the Inflatable Carpet down to 1.4, close to the acceptable level. For all other test conditions, the tibia index was reduced well below 1.3 by the Inflatable Carpet. The device could therefore be one of the measures car makers can take in order to meet the requirements of the new European frontal test procedure, to minimize the tibia index.

This study has not evaluated any more interaction between the foot and a pedal, for example the brake pedal, than the effect of the contact velocity between the foot and the toe pan. There can also be other effects that contribute to the loading of the foot/ankle and the lower leg. A few tests with the right foot of the dummy on a fully depressed brake pedal (rigidly attached to the toe pan) were run in addition to the tests according to the test matrix. The toe pan acceleration was 70 g. The results indicate that the loadings to the foot and tibia were not worse than at the "clearance" position of the foot, rather the opposite. However, more testing is needed before any conclusions can be drawn.

Klopp et al. (1997) found that the peak contact plantar force, its onset rate, and the peak heel acceleration were good predictors of injury to the lower limb. The fifty percentile probability of injury were found to be at 9.3 kN

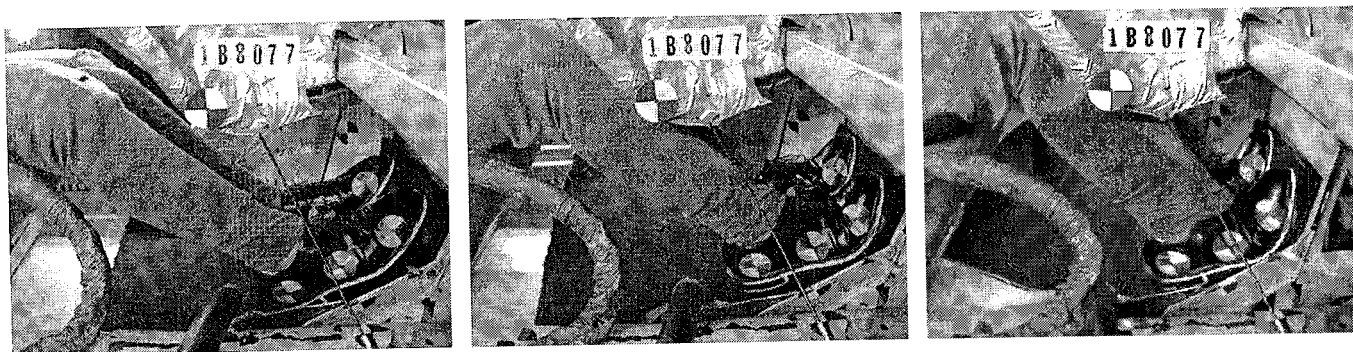
peak contact force, 5 kN/ms peak contact force onset rate, and 216 g peak heel acceleration. If it can be assumed that the tibia force, measured with the Hybrid III dummy lower leg, can substitute the plantar contact force, it is noticeable that not only is the tibia force significantly reduced by the Inflatable Carpet but also the onset rate. Figure 6 shows the tibia force time histories for test no. 79 and test no. 80, with and without the Inflatable Carpet respectively, with the "clearance" foot position and 140 g toe pan acceleration. The maximum onset rate of the tibia force was reduced from a maximum of 6 kN/ms without the Inflatable Carpet to only 2 kN/ms with it. This reduction of the onset rate due to the Inflatable Carpet should therefore also contribute to the reduction of the risk of receiving an injury to the lower limb in collisions with violent footwell intrusion.



**Figure 6. Examples of tibia force onset rates. In test no. 79 (with InCa) max 2 kN/ms at 43 ms and in test no. 80 (without InCa) max 6 kN/ms at 41 ms.**

The dorsiflexion motion of the foot could be evaluated from the high speed video recordings from the tests. It was found that the motion was at maximum 20 degrees from the start position (Figure 7, left picture) in tests with the Inflatable Carpet. The motion was somewhat less in tests without the Inflatable Carpet. Inversion and eversion motions were very small. Parenteau (1996) found in her research that the dorsiflexion motion could be up to 44° (+/- 10°) without failure in the ankle joint. The results from the tests in this study thus indicates that the Inflatable Carpet does not increase the risk of injury to the ankle. The motion of the toes were large (Figure 7, right picture). It was not possible to evaluate whether this could be injurious to the mid foot bones and ligaments. However, the bending of the toes was not larger with the Inflatable Carpet than without.

Typical values for the femur loads were 2 to 4 kN. They were not significantly influenced by the different toe pan accelerations or the use of the Inflatable Carpet.



Initial position  
(0 ms)

InCa fully inflated  
(35 ms)

Max. toe pan intrusion  
(45 ms)

**Figure 7.** The sequence of pictures from test no. 77 shows the inflation of the Inflatable Carpet and the toe pan intrusion (80 mm).

Static deployment tests of the Inflatable Carpet have previously been performed at Autoliv Research, to study the effect on the feet and lower legs, when the feet are placed against the toe pan, a kind of out of position (OOP) situation. In these tests, foot accelerations and tibia forces of maximum 20 g and 1 kN respectively were measured. These values are low compared to known IARVs, hence the Inflatable Carpet itself should be harmless.

## CONCLUSIONS

The study has shown that the test method with a mechanical simulation of toe pan intrusion works well. The acceleration of the toe pan, the position of the foot relative to the toe pan and the use of the Inflatable Carpet, all significantly influenced the load on the foot and the lower leg:

- An increase of the toe pan acceleration from 70 g to 140 g doubled the foot acceleration, and the tibia force increased 35 to 90 % (without the Inflatable Carpet).
- A clearance between the foot and the toe pan (simulating a foot on a pedal), instead of in contact with the toe pan, increased the foot acceleration by 2 to 3 times and the tibia force by up to 70 % (without the Inflatable Carpet).
- The use of the Inflatable Carpet reduced the foot acceleration by up to 65 % and the tibia force by up to 50 %.
- The tibia index (upper tibia) was reduced by 30 to 60 % by the Inflatable Carpet.

The Inflatable Carpet therefore seems to be able to significantly reduce the risk of receiving an injury to the foot/ankle and lower leg in collisions, where violent footwell intrusion occurs.

## ACKNOWLEDGEMENT

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# CRASHWORTHINESS OF ALUMINUM STRUCTURED VEHICLES

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## ABSTRACT

Today, due to concerns about the emission of greenhouse gases and the Kyoto Protocol, there is increasing interest in the use of aluminum for reducing the weight of passenger cars to reduce fuel consumption and exhaust emissions, particularly CO<sub>2</sub>. In recent years, several aluminum structured cars have been developed and are in service in various parts of the world, all of which have met the relevant vehicle safety requirements. However, concern continues to be raised about the crashworthiness of light weight vehicles. This paper will summarize data on the energy absorption of aluminum automotive materials and structures under impact collapse conditions as well as published information from the automotive industry on the crashworthiness of two aluminum intensive vehicles. The data and crash results demonstrate that aluminum structured vehicles can be designed to be crashworthy and to provide at least the same level of occupant protection as equivalent steel structured vehicles but at about half the vehicle structure weight.

## 1. Introduction

In recent years, more and more car companies have been exploring the use of aluminum for vehicle structures for reducing the weight of their cars, primarily to reduce fuel consumption and consequently CO<sub>2</sub> and other emissions. However, they have also seen other benefits such as improved performance without having to increase engine capacity and excellent road holding, handling and NVH (noise, vibration and harshness) characteristics, as a result of the body stiffnesses that are being achieved with both space frame and weld-bonded stamped sheet construction.

Several low volume production vehicles with aluminum structures have been introduced in recent years such as the Honda NSX<sup>(1)</sup>, the Audi ASF A8<sup>(2)</sup> and the General Motors EV1<sup>(3)</sup>. In addition, Ford has built a test fleet of 40 AIV's (Aluminum Intensive Vehicles) based on the design and mechanical components of its highly successful DN5 Taurus/Sable volume production mid-sized sedan<sup>(4)</sup>. Most recently, Ford has developed its P2000 PNGV (Partnership for a New Generation of Vehicles) prototype, a purpose-designed aluminum intensive mid-sized sedan. It has the same passenger and luggage space as the DN5 Taurus and better performance but weighs just 2000lb (908kg) compared with the 3318lb (1505kg) of the current steel production DN101 Taurus<sup>(5)</sup>. All of these vehicles are significantly

lighter than corresponding steel structured vehicles and especially the P2000 where Ford took full advantage of the primary weight saving from the aluminum body-in-white structure to reduce the weight of all the vehicle's secondary systems.

Driving these various vehicles reveals that they have all of the merits noted above for aluminum structured vehicles. What is not apparent and hopefully will not be experienced by driving one of these or the other aluminum structured cars that have been introduced in recent times is that they all have excellent crashworthiness. Clearly, no car manufacturer would build and sell or release for road use any vehicle that does not meet or exceed all the accepted standards for occupant safety, but there is, nevertheless, public concern that vehicles with reduced weight also have reduced crashworthiness.

There is evidence that reducing the weight of conventional cars by downsizing does reduce safety<sup>(6)</sup> but one of the major advantages of aluminum for vehicles structures is that significant weight saving can be achieved without downsizing. In particular, the length of the front and rear end crumple zones which provide the major crash energy protection system for passenger vehicles, can be maintained without adding significant extra weight.

The purpose of this paper is therefore to bring together the key test results and data for aluminum automotive materials, structural assemblies and aluminum structured vehicles pertaining to energy absorption. Taken together, this information unequivocally demonstrates that aluminum materials, when used with appropriate design approaches, are excellent materials for safely absorbing vehicle kinetic energy and therefore for building crashworthy light weight vehicle structures. In developing this paper, the author acknowledges the liberal use he has made of the benchmark data generated by present and former colleagues with Alcan. However, before presenting this information, a brief description will be given of the two major design approaches that have been used to build aluminum structured vehicles.

## 2. Aluminum Vehicle Design Approaches

### 2.1 Stamped Sheet-Based Structures

The stamped sheet or unibody design for aluminum structured vehicles is based on the approach used today with steel for essentially all high volume production vehicles and where designs have been gradually optimized to reduce mass and enhance structural stiffness, the latter being important for good handling and drivability. Honda employed this approach for the NSX, using a combination of spot and MIG spot welding to join the structure together. However, due to the lower modulus of aluminum, the body structure weight saving was limited to 40% compared with an equivalent steel design. A breakthrough came for aluminum with the development by Alcan of its Aluminum Vehicle Technology (AVT) structural bonding system using an Al-3%Mg structural sheet material (AA5754-0)<sup>(7)</sup>. The structural bonding significantly increases the body structure stiffness, particularly the torsional stiffness. In turn, this enables the weight saving compared to steel to

be increased to over 50%, thereby improving the economics for using aluminum by reducing the weight used and also by giving enhanced torsional stiffness compared to spot welded steel, exceptional fatigue endurance and, as will be discussed later, enhanced impact energy absorption.

The AVT system was first used in a production vehicle for the front longitudinal crash energy management beams for the Jaguar Sport XJ220, a limited production, high performance sports car. The major applications to date are for General Motors' EV1 production electric car, for Ford's AIVs and, most recently, for Ford's P2000 PNGV prototypes. The weld-bonded aluminum body-in-white structure of the Ford AIV is shown in Figure 1.

### 2.2 Aluminum Space Frame Structures

The aluminum space frame approach for light weight vehicle structures was pioneered by Alcoa (8) and Norsk Hydro<sup>(9)</sup> and has been further evolved by Alumax<sup>(10)</sup> and by Lotus Cars<sup>(11)</sup>. In this approach, structural frames are built using shaped or formed aluminum extrusions which are joined by a variety of methods such as fusion welding to cast connecting nodes (Alcoa), sectioning and direct fusion welding (Norsk Hydro), compression fit forming (Alumax), and adhesive bonding supplemented by mechanical fasteners (Lotus Cars).

The first aluminum space frame production car was the Audi ASF A8. Figure 2 shows the space frame of the A8 and note the extruded tubular members at the front of the main longitudinal rails which are designed to fold like concertinas in the event of a severe collision to provide impact energy absorption. Other examples of space frame vehicles are the Renault Spider with the Norsk Hydro approach, the Lotus Elise, the Panoz Roadster (Alumax) and the Plymouth Prowler (Alcoa).

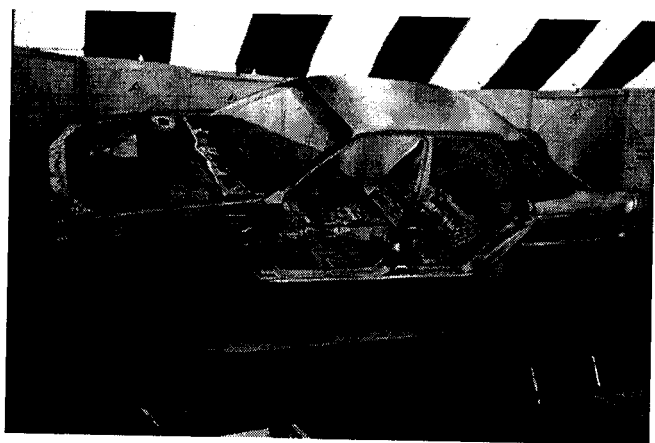


Figure 1. Ford AIV body-in-white

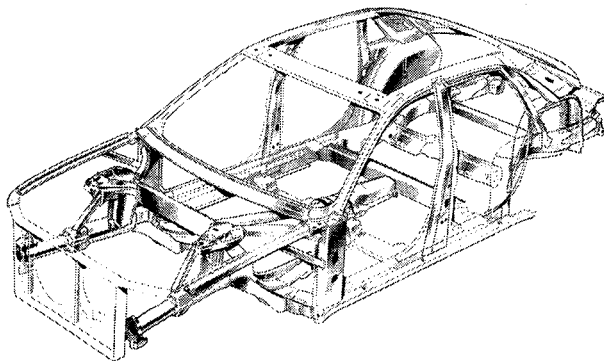


Figure 2. Aluminum space frame for the Audi A8

### 3. Energy Absorption and Vehicle Design

In both sheet unibody and space frame vehicles, the aluminum structure provides the main safety cage to protect the vehicle occupants and is therefore designed to remain essentially intact in a collision while the front and rear extensions of the aluminum structure (except for the Lotus Elise) are designed to collapse by concertina-type folding or controlled deep bending collapse to absorb the kinetic energy in the collision. In these two modes of deformation and hence of energy absorption, aluminum behaves exactly like steel and therefore essentially the design approach and design formulae used for steel can be used for designing crashworthy aluminum structures, provided that the appropriate mechanical properties are used.

Figure 3 shows how an aluminum structural box beam collapses by concertina folding under impact loading and Figure 4 shows the crush load for such a box beam as a function of crush distance, the "area" under the curve representing the energy absorbed. In this type of behaviour, aluminum mirrors exactly the behaviour of steel as shown in Figure 5. Concertina folding of the front and rear main structural beams is the preferred means of absorbing collision impact energy in both steel and aluminum vehicle structures since this mode of collapse provides the highest energy absorption per unit length of collapse and is also the most predictable. Thus

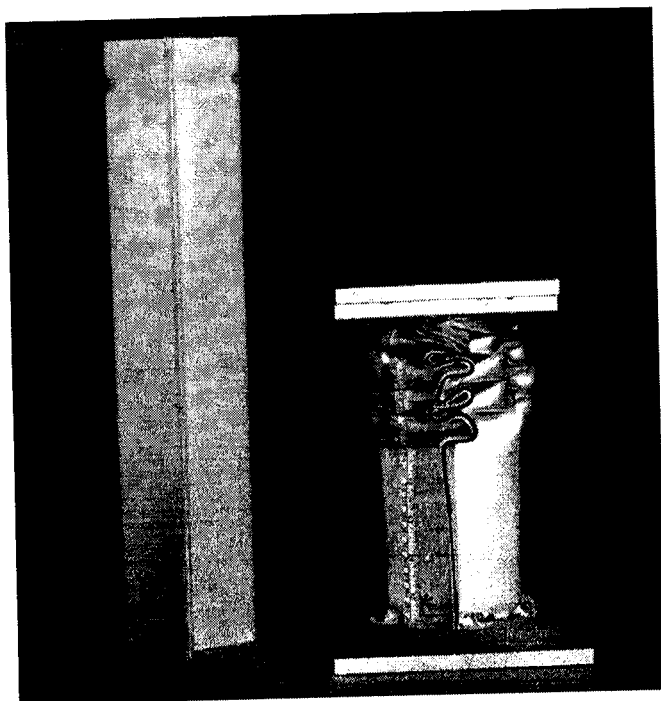


Figure 3. Aluminum hexagonal box beam before and after impact.

vehicle designers go to considerable lengths to promote this mode of collapse, even for off-centre frontal impact situations.

The challenge for the vehicle designer is to design the vehicle structure and particularly the front end structure so that this collapses progressively from the front. Thus the back-up structure behind the primary energy absorbing structure must not collapse prematurely, nor must it buckle and so prevent the front members from performing their energy absorption role and yet it too may be required to collapse during the latter stages of a collision. The structure designer may also elect to have the upper front rails absorb some of the impact energy but here the designer must ensure that these do not transfer too much load to the upper green house structure and cause this to collapse. These design considerations are beyond the scope of this paper and the reader is referred to the Washington-based Aluminum Association's Automotive Aluminum Crash Energy Manual<sup>(12)</sup>.

### 4. Mechanical Properties and Impact Collapse Behavior

#### 4.1 Mechanical Properties - Sheet Materials

Table 1 shows the typical mechanical properties of the two most commonly used aluminum automotive sheet materials with the corresponding properties of mild steel. Of the aluminum materials, AA5754-O is the

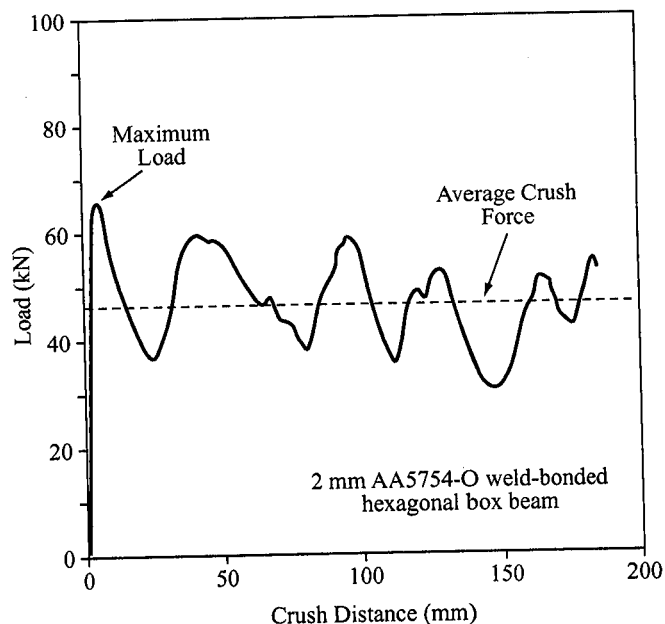
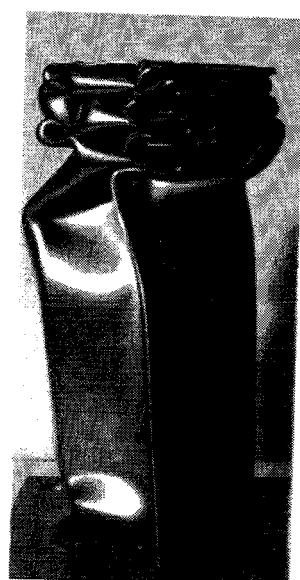


Figure 4. Force-displacement curve for slow crush testing of an aluminum hexagonal box beam.



1.2 mm spot-welded  
steel section



2.0 mm weld-bonded  
aluminum section

Figure 5. Comparative folding patterns for steel and aluminum hexagonal box beams

structural material that is used with the Alcan AVT system and has medium strength, high formability and exceptional thermal stability. AA6111-T4 has higher strength and the capability to further strengthen during a paint and or adhesive thermal cure treatment and is now the most commonly used aluminum material in North America for outer closure panels. However, it has a lower overall formability than AA5754-O and is not as thermally stable but, nevertheless, is used in certain structural applications where high strength is required and where there will be no long term exposure to elevated temperatures.

From Table 1, it is evident that the density of aluminum is just about one third that of steel, with the net result that with an aluminum sheet structure that is 50% the weight of an equivalent steel structure, the aluminum will be, on

average, 50% thicker. Since the main mode of material deformation in the collapse of vehicle structures is by folding, aluminum has an advantage over steel in that, with its thicker gauge, relatively more deformation will be occurring in the aluminum as it folds and hence more of the material becomes involved in the energy absorption. This is offset to some extent by the higher strength of steel but it will be shown that with a weld-bonded structure, the same crash energy absorption as steel is achieved with a weight saving of ~ 45%.

#### 4.2 Mechanical Properties—Aluminum Extrusions

The aluminum AA6xxx (Al-Mg-Si) alloys are the preferred ones for extrusions for automotive space frame structures due to the ease of extrusion, good formability, excellent corrosion resistance and good weldability. These alloys provide good strength at low cost, are readily formed in the T4 temper (as extruded, quenched and naturally aged) and can be used in this temper or can be artificially aged to the T5 or T6 temper to give higher strengths. Of the alloys used in space frame structures, AA6063 has the lowest strength, followed by the medium strength AA6005, 6005A and AA6061 and the high strength AA6082. The mechanical typical properties of these materials are given in Table 2.

The alloys commonly used in space frames for crash energy absorption are 6063, 6005A and 6061. The alloy 6082 is not recommended for this function because it is too strong and has a tendency to crack during folding collapse<sup>(13)</sup>. As with AA6111 sheet material, some consideration must be given to the material temper that is used, especially where crash energy absorption components will be exposed to elevated temperature during vehicle service. However, as is well documented by Court et al<sup>(13)</sup>, this concern can be eliminated by overaging the materials to the T7 temper using typically 8 hrs at 210°C. This reduces the strength level from the fully age hardened condition (T6) but improves the ductility, toughness and eliminates any tendency to

Material	Elastic modulus (MPa x 10 <sup>3</sup> )	Density (kg/m <sup>3</sup> x 10 <sup>3</sup> )	Yield strength (MPa)	UTS (MPa)	Elongation (%)
AA5754-O	70	2.7	100	220	23
AA6111-T4*	70	2.7	180	320	25
Mild steel	205	7.85	220	370	39

\*after adhesive cure treatment (~30 min at 180°C)

Table 1. Typical material properties of aluminum and steel automotive sheet materials

crack during impact folding while providing excellent strength stability, even with long-term exposure to above ambient temperatures.

### 4.3 Material Strain Rate Sensitivity

It is generally accepted that aluminum alloys exhibit virtually no strain rate sensitivity but tensile tests carried out at strain rates appropriate to the collapse of impact box beams (3 to 64s-1) shows that the yield strength of AA5754 increases by about 25%. In turn, this is reflected for example in a 10% increase in the crush force at an impact velocity of 12m/s compared with that for a slow crush<sup>(14)</sup>, that is, there is a dynamic factor for this situation of 1.1.

## 5. Box Beams in Axial Collapse

### 5.1 Energy Absorption

Table 3 shows the impact energy absorption for both spot welded and weld-bonded hexagonal section box beams in 2.0mm AA5754-O and for a dimensionally similar 1.2mm gauge mild steel box beam. With the aluminum beams, there is a beneficial effect from the weld-bonding which results in about a 15% increase in energy absorption and is due to the adhesive bonding causing tighter folds and hence more metal deformation. The net result is that weld-bonding with AA5754 beams gives comparable energy absorption to spot welded mild

steel at about 55% of the steel weight.

The effect of testing the weld-bonded box beam at below ambient temperature is also shown in Table 3 where it is apparent that the energy absorption is enhanced at these temperatures. Experiments on the effect of the aluminum gauge indicate that the average crush force is proportional to the material gauge to the power of 1.6. In turn, this gives the energy absorbed per unit mass proportional to the gauge to the power of 0.6<sup>(14)</sup>.

The effect of beam section geometry is illustrated in Table 4 and, as would be expected, essentially mirrors the shape effect found with steel box beams. This table illustrates the beneficial effects of having multiple corners in a beam section since this is where the major deformation occurs during crush. Hence the increased energy absorption of the hexagonal section compared with the top hat section. The table also shows the beneficial effect of using the higher yield strength of the T6 temper compared with the T4 temper for AA6063 extrusions. However, as noted earlier, cracking problems can be encountered with the higher strength 6xxx alloys in the T6 temper.

### 5.2 Predicting Axial Collapse Energy Absorption

Several methods have been developed for predicting the

Alloy	Elastic modulus (MPa x 10 <sup>3</sup> )	Density (kg/m <sup>3</sup> x 10 <sup>3</sup> )	Yield strength (MPa)	UTS (MPa)	Elongation (%)
6063-T4	69	2.7	90	172	23
6063-T5			145	185	12
6063-T6			215	240	12
6005A-T4	69	2.7	115	215	22
6005A-T5			265	290	12
6005A-T6			265	290	12
6061-T4	69	2.7	145	240	22
6061-T5			270	300	10
6061-T6			275	310	12
6082-T4			150		21
6082-T6			310	330	8

Table 2. Typical mechanical properties of automotive extrusion alloys

Material and joint type	Average crush force (kN)	Mass relative to steel section mass (%)	Specific energy absorption (kJ/kg)
1.2 mm Mild steel Spot-welded (25 mm pitch)	52	100	14.5
2.0 mm AA5754-O Aluminum Spot-welded (25 mm pitch)	46	57	22.4
2.0 mm AA5754-O Aluminum Weld-bonded (75 mm pitch)	53*	57	25.8

\*Average crush force (kN) 57.4 at -10°C, 58.7 at -40°C

Table 3. Comparison of impact results for aluminum and steel hexagonal box beams


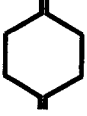
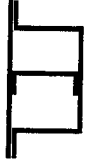
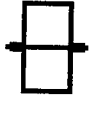
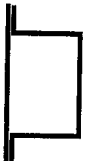

Material	2.6 mm AA5754-O sheet					AA6063	
Geometry							
						Extrusion	
Average crush force (kN)	85	80	95	82	60	T4 34	T6 58
Mass-specific energy absorption (kJ/kg)	29.9	29.5	28.8	24.8	22.5	16	28

Table 4. Effect of aluminum section geometry on axial crash performance.

average crush load for box beams, the wave length of the fold pattern and the maximum force necessary to initiate the collapse process. The latter is important because it determines the strength required in the back-up structure. However, as with steel impact members, initiators are commonly used to limit this force and to control the starting pattern for the folding collapse.

It is not the intention in this paper to go into the modelling approaches that have been developed and here reference can be made to The Aluminum Association's Crash Energy Manual<sup>(12)</sup> or to McGregor et al<sup>(14)</sup>. However, it is worth mentioning a relatively simple PC based package called CRASH-CAD developed by Wierzbicki and Abramowicz<sup>(15)</sup>. Table 5 shows the excellent agreement between actual experimental results and predictions for a version of CRASH-CAD modified for aluminum for both the average crush force and the fold half-wavelength for four different AA5754 spot welded box beams. Accurate prediction of the fold half-wavelength is valuable since it shows the spot welding spacing required to facilitate the development of the folding pattern.

## 6. Bending Collapse

Bending collapse is the other main deformation mode that has to be considered by designers in establishing crashworthy vehicle structures. The key parameters are the maximum bending moment to initiate collapse, the energy absorbed and the mode of failure.

Failure can be by local buckling, which is typical for

beams with a high width-to-material thickness ratio and is a stable and reliable mode, but the peak bending moment and the energy absorbed are low. Failure can also be by tensile tearing; this gives the highest maximum bending moment and energy absorption but there is no residual load carrying capacity after failure. This mode of failure is not common with aluminum but can occur in beams with small width to material thickness ratios. The third and most desirable failure mode is delayed buckling where buckling does not occur until the material is well into its plastic range, and such beams represent the most weight-efficient design. All three modes are shown in Figure 6.

A comparison of the energy absorption for weld-bonded beams in 1.8mm AA6111-T4, 2.0mm AA5754 and 1.2mm spot welded mild steel is shown in Figure 7 along with a schematic of the beam design. Here the tests were conducted with the crown in compression. It can be seen that the steel and the AA5754 gave similar results with the aluminum giving a 45% weight saving while the AA6111 gave the highest moment and energy absorption and represents a weight saving of 50% compared with the steel.

With bending collapse, the results obtained depend on whether the crown is in tension or in compression and also whether spot welding or weld-bonding is employed for joining. In general, it is desirable to use weld-bonding for beams fabricated from sheet and to arrange to have the crown in compression for the most likely bending collapse situation. Clearly, the above results

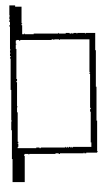
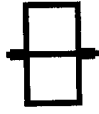
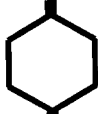
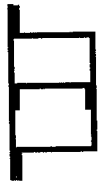
Geometry 2 mm AA5754-O spot-welded					
Average crush force (kN)	CRASH-CAD	28.1	53.2	41.9	66.6
	Experimental	26.0	49.6	39.8	70.1
Fold half- wavelength (mm)	CRASH-CAD	35.9	32.4	36.0	46.1
	Experimental	37.5	33.5	36.5	41.5

Table 5. Comparison of predicted and measured crush performance using CRASH-CAD for various aluminum section geometries

also apply to the bending collapse of extruded aluminum beams, with these behaving much like weld-bonded beams fabricated from sheet.

Reference can be made to the paper by Meadows et al for more details on the collapse behavior of beams in bending<sup>(16)</sup>. However, the major conclusion is that, with appropriate designs, aluminum automotive structural materials can provide the same energy absorption in bending collapse as steel at weight savings of 45 to 50%.

## 7. Barrier Crash Data for Aluminum Structured Cars

Clearly, any car that is sold into the market must meet the relevant government safety standards but the actual crash test data is not usually available. However, Ford

has released the frontal barrier crash results for a 35mph (56km/h) impact speed for one its AIV's along with the corresponding data for the regular steel production DN5 Taurus on which the design of the AIV was based<sup>(17)</sup>. This data is given in Table 6 along with the appropriate FMVSS (US Federal Motor Vehicle Safety Standard) 208 requirements for occupant crash protection. It is evident that the AIV essentially matched or improved on the performance of the regular steel production vehicle and also that both vehicles comfortably exceeded the FMVSS 208 requirements which, it should be noted, only requires at crash test speed of 30mph.

Data for a full vehicle frontal crash test conducted on the Audi A8 4.2litre at 54.8km/h (34mph) have also been released<sup>(12)</sup> and are reproduced in Table 7. Again, the

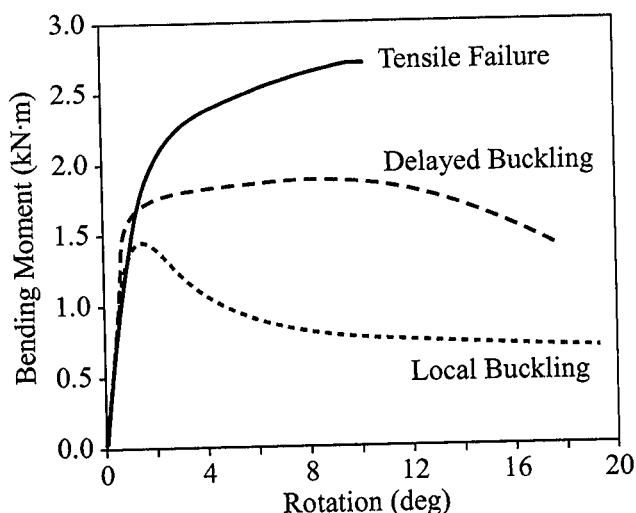


Figure 6. Moment-rotation curves, showing the three failure modes, for aluminum beams under bending

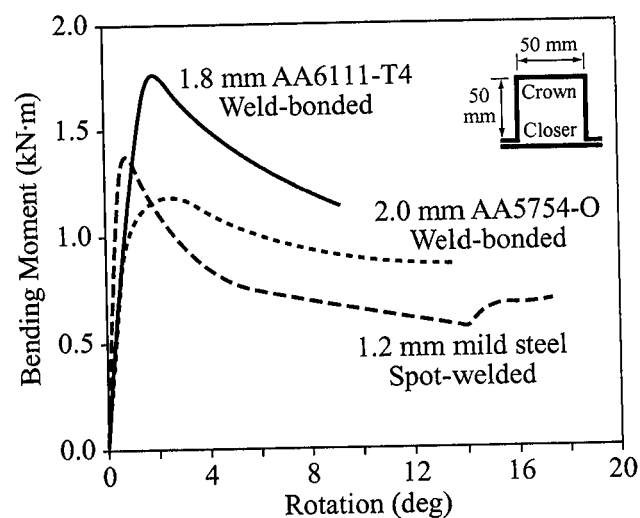


Figure 7. Comparison of aluminum and steel sections under bending with crown in compression.



	AIV	Steel (DN5)	FMVSS 208 Req.
Dynamic crash (in)	30.8	28.4	—
Head Injury Criteria (HIC)	549	524	1000
Chest acceleration (g)	37	53	60
Chest displacement (in)	1.4	1.4	3.0
Torso belt load (lb)	1219	1686	—
Left femur load (lb)	697	1644	2250
Right femur load (lb)	906	1092	2250

Table 6. Frontal barrier crash results for Ford AIV and DN5 Taurus.

	Driver	Passenger	Low Risk Injury Values
Head Injury Criteria (HIC)	531	424	< 1250
Head acceleration (g)	61	54	≤ 90
Head pitch angle (°)	40	50	—
Chest acceleration (g)	56	57	≤ 60
Pelvis acceleration (g)	61	66	≤ 55 (56–75*)
Force on thighs (lb)	530	587	≤ 1349

\*medium risk

Table 7. Frontal crash barrier data for 54.8 km/h impact for Audi A8

numbers are well below the FMVSS requirements and, where comparisons can be made, the results for the Audi A8 are very similar to those for the Ford AIV.

## 8. Conclusions

1. A number aluminum structured passenger cars have been developed and introduced into the market place with body structure weight savings of 45-50% compared with conventional steel structured cars.
2. The aluminum sheet and extrusion materials that have been developed for automotive body structure applications absorb vehicle kinetic energy from severe collision events by material folding in just the same way as the steels that are used today in vehicle construction.
3. Typically, the aluminum materials are used at gauges 50% thicker than mild steel and this increased thickness results in more material deformation in the folding process. This offsets the higher strength of steel and allows aluminum beams in both axial and bending collapse to absorb the same amount of crash energy as steel at weight savings of ~45 to 50%.
4. Design guidelines have been developed for energy absorbing members for both unibody sheet and extruded space frame structures and various modelling techniques have been developed to predict the energy that

aluminum box beams will absorb. These allow effective designs to be quickly developed without the need for exploratory building and testing.

5. Published crash test results at ~55 km/h for two typical aluminum structured cars, one of unibody construction and the other a space frame design, show that these have excellent crashworthiness. In fact, both these aluminum structured cars well exceeded the US FMVSS 208 30mph (48.3km/h) occupant crash protection requirements, even at the higher test speed used.

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# OFFSET CRASH TESTS - OBSERVATIONS ABOUT VEHICLE DESIGN AND STRUCTURAL PERFORMANCE

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## ABSTRACT

Offset frontal crashes can place severe demands on the structure of vehicles. Offset crash tests conducted in the USA, Europe and Australia are revealing that some vehicle models perform exceptionally well in these severe tests. Between them, the authors have been involved in the assessment of more than 45 offset crash tests conducted under the Australian New Car Assessment Program (ANCAP). They have also evaluated data on a similar number of offset crash tests conducted in the USA and Europe.

This paper sets out some general observations about the structural performance of cars, passenger vans and four-wheel-drive vehicles in offset crash tests. The design features which appear to contribute to good structural performance are discussed. Likely reasons for poor performance are noted.

## INTRODUCTION

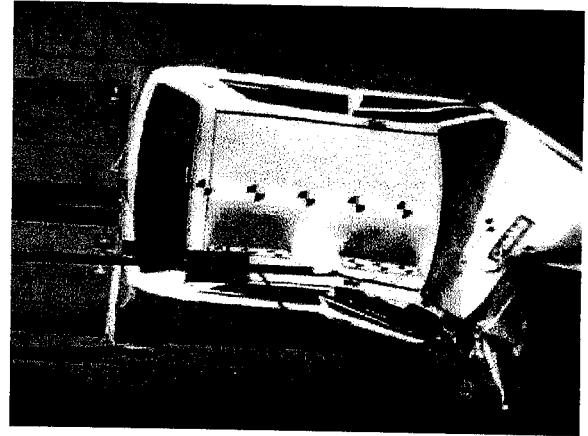
This paper sets out some general observations about the structural performance of cars, passenger vans and four-wheel-drives in the offset crash test conducted by Australian NCAP (New Car Assessment Program), the US Insurance Institute for Highway Safety (IIHS) and Euro-NCAP. The observations are intended to be constructive and should assist vehicle designers improve the crashworthiness of vehicles.

### The Offset Crash Test

In the offset crash test the vehicle is travelling at 64km/h when it collides with a crushable aluminium barrier. The barrier initially makes contact with 40% of the width of the front of the vehicle, on the driver's side (Lowne 1996). The resulting crash forces place severe demands on the structure of the vehicle, particularly on the driver's side.

The vehicle structure affects the outcome of an offset frontal crash in two main ways:

- i. Absorption and dissipation of crash energy
- ii. Integrity of the passenger compartment



**Figure 1. Overhead view of an offset test into a deformable barrier at 64km/h (ANCAP).**

## ABSORPTION OF CRASH ENERGY

The offset crash test is intended to simulate a collision between two similar-sized vehicles with similar crush characteristics. In these types of crashes it is desirable that most of the crash energy is absorbed and dissipated in the deformation of components within the front metre or so of each vehicle.

The increasing use of engine/suspension cradles has allowed designers to better control this deformation and to by-pass very rigid components such as engine blocks which are not effective energy absorbers.

To avoid load concentrations it is important that the crash forces are spread across the face of the deformable barrier. In several cases it has been observed that box-section structures at the front of the vehicle have punched through the barrier and relatively little energy is absorbed through deformation of the barrier. These box section structures appear to be designed to achieve better performance during a full-frontal crash into a rigid barrier but they can be much less effective during offset crashes into deformable objects, including other motor vehicles. Conversely, some box sections which crush efficiently in a full-frontal crash do not perform as well under the asymmetric loads of an offset crash - they tend to buckle rather than concertina.

Some four-wheel-drive recreational vehicles have relatively stiff front structures. This can result in a very high deceleration of the passenger compartment and high loads on the occupants. A stiff front structure can also place excessive demands on the deformable barrier,

causing the barrier to bottom out early in the crash sequence. In a collision between two vehicles the occupants of the heavier vehicle would generally be better off, due to the physics of the collision. In the case of four-wheel-drive vehicles colliding with passenger cars, however, this advantage can be diminished by a stiff front structure. Analysis of crashes in Australia have shown that, on average, the driver of a four-wheel-drive vehicle has a greater likelihood of being killed or seriously injured in a crash than the driver of a large car (Newstead et al, 1997).

### Aggressivity

The front structure of a vehicle also has a strong influence on aggressivity - the degree to which individual vehicle models cause injuries to occupants of other vehicles. The Monash University Accident Research Centre (MUARC) has recently conducted an analysis of aggressivity in more than 300,000 on-road crashes (Cameron et al 1998). Key results related to front structure are set out below:

- There is the expected trend of increased aggressivity with increased vehicle kerb mass but there is a large amount of scatter, with some high-mass vehicles showing low (good) aggressivity.
- Four-wheel-drives generally show high aggressivity but there is a large amount of scatter and some commendable exceptions. Some of the lighter four-wheel-drives are no more aggressive than cars of the same mass.
- Passenger vans and commercial vans tend to have high aggressivity for their kerb mass.

The cases where, in the offset crash test, the front structure imposed concentrated loads on the deformable barrier could also be expected to be hazardous to the occupants of other vehicles due to increased penetration and intrusion. This might partly explain the adverse result for vans. Other factors might be the very high proportion of these vehicles fitted with "bull bars" in Australia (estimated at 50% or higher - Traffic and Transport Surveys, 1994) and the higher laden mass, compared with cars (the analysis was based on kerb mass).

One criticism of consumer offset crash tests is that they are claimed to push manufacturers towards building stiffer vehicles, in order to protect their own occupants, and that these stiffer vehicles are more aggressive to other vehicles. The MUARC study, and results of recent offset crash tests suggest that this criticism is unfounded. Some vehicles performed exceptionally well at protecting their occupants in the offset test while apparently having low aggressivity towards the occupants of other vehicles. Evidently this was achieved by efficiently absorbing crash energy in the front structure while retaining the integrity of the passenger compartment.

Occupants of other vehicles should be at less risk in collisions with these low-aggressivity vehicles. Vehicle design is therefore a crucial factor in achieving good crashworthiness *and* low aggressivity.

If the all-vehicle average aggressivity observed in the MUARC study had been reduced to the average for small cars then it is estimated there would have been a 30% reduction in fatal/serious injuries to the occupants of "other" vehicles. Since aggressivity is not a quality easily affected by consumer pressure this may be an area which requires legislation.

### INTEGRITY OF THE PASSENGER COMPARTMENT

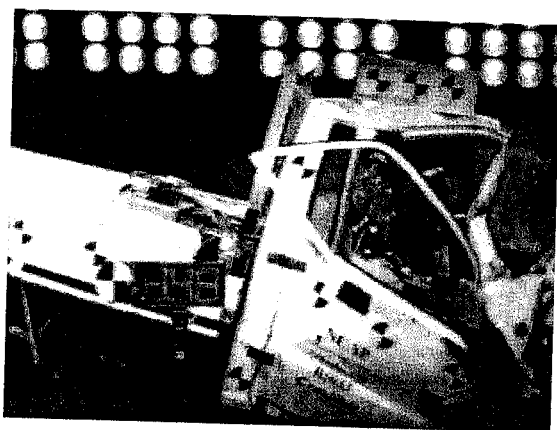
The passenger compartment should keep its shape in the crash test. The steering column, dash, roof, roof pillars, pedals and floor panels should not be pushed excessively inwards, where they are more likely to injure the occupants. Doors should remain closed during the crash and should be able to be opened after the crash to assist quick rescue.

There is a temptation, when observing a frontal crash test, to concentrate on what is happening at the front of the vehicle, since this is where most of the deformation is occurring. This might give the impression that the front of the vehicle is being forced back into the passenger compartment. While this is an important source of passenger compartment intrusion it is only part of the story.

At the height of a frontal crash test the front of the vehicle has come to a halt but the remainder of the vehicle is still undergoing a high deceleration - typically around 40g (up to 60g with some four-wheel-drive vehicles). Substantial compression forces are generated between the front and rear of the vehicle at this time.

Consider a transverse vertical plane in line with the dash. The resulting cross-section might include the a-pillars, side doors, door sills and floor. About 50% of the vehicle's weight will usually be rearward of this plane. The compression forces arising in these components due to a 40g deceleration are therefore equivalent to about 20 times the weight of the vehicle. This places a severe demand on the structure. Furthermore, there is usually very little structural redundancy in the design and if any one of these components has a major failure then catastrophic collapse can occur (and has been observed).

For commercial vehicles and four-wheel-drives the proportion of mass in the rear is usually greater than with passenger cars, particularly when laden. This, combined with a stiffer front structure, can place a very severe demand on the structure of the passenger compartment.



**Figure 2. Unladen light commercial vehicle during an offset crash test at 64km/h (ANCAP).**

During the 56km/h full-frontal test of several four-wheel-drive vehicles there was a noticeable sleeving effect, where the sides of the passenger compartment tended to slide around the engine compartment, resulting in substantial firewall and dash intrusion at the height of the crash (figure 3). The deformation usually appears to be elastic and therefore the post-crash residual movement of the firewall and dash might not indicate a problem.



**Figure 3. Overhead view of a full-frontal crash test into a solid barrier at 56km/h (ANCAP).**

#### **Footwell intrusion**

Front suspension components such as lower control arm pivots are commonly located on, or just ahead of, the footwell toe-pan area and above the floor level. The suspension components which are attached to these points are usually rigid in a longitudinal direction and therefore, during the crush of the front of the vehicle, they tend to push the mounting points rearwards into the toe-pan. In addition to the risk of lower leg injury due to intrusion, dynamic movement of the toe-pan can cause the legs to lift

suddenly, sometimes resulting in a violent head to knee strike.

The better designs tend to locate the suspension mounting points below floor level. In this configuration longitudinal structural members mounted under footwell area can effectively transmit the crash forces past the footwell area and reduce intrusion - this has been observed on several vehicles. However, in some cases such structures have insufficient strength to cope with forces during a 64km/h offset crash test. One possible weakness is the location of joints or welds at a bend or change in cross-section.

These observations also apply where engine and/or suspension components are mounted on a cradle under the front of the vehicle. These cradles are usually attached to the body just ahead of the toe-pan. Their height and method of attachment can have a significant influence on footwell intrusion.

Road wheels and tyres are relatively rigid when compared with footwell panels and they can contribute to intrusion into the footwell area or separation of footwell panels. Failure of the seams between the floor and door sill or the firewall and a-pillar can greatly reduce the strength of this region.

#### **Seat movement**

Another factor associated with floorpan deformation is the movement of seats. In some cases seats have tilted forward and/or to the side by substantial amounts when the floorpan or transmission tunnel deforms. This can have an adverse effect on occupant kinematics. This is particularly a concern where the seat belt buckle is mounted on the seat because it can result in extra forward movement of the occupant - thereby defeating the advantage of mounting the buckle on the seat (better adjustment of the seat belt to suit the occupant).

With seat-mounted seat belt buckles the loads on seat components are much higher. Seat runners have been observed to bend, seat mounting frames have rocked forward and floor panels have deformed. All these problems have contributed to excessive forward movement of the occupants.

#### **Upward movement of the steering wheel**

Several of the crash-tested passenger vans and utilities experienced a large upward movement of the steering column during the crash test. In some cases the whole dash appeared to rotate upwards taking the steering column with it. In other cases the vehicle structure near the bottom end of the steering column was pushed rearwards, causing the column to rotate and move upwards. Where an airbag is fitted this movement can adversely affect its

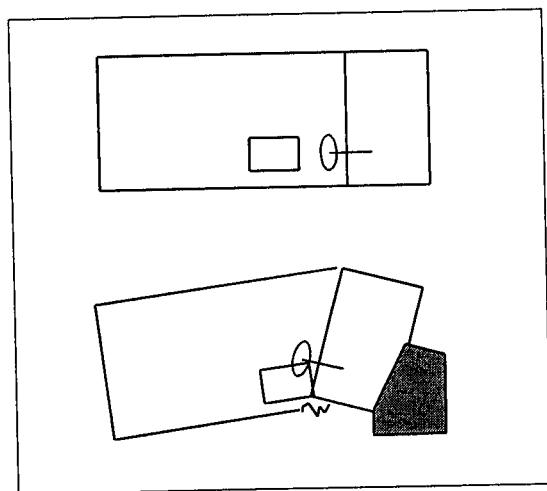
performance (this is evident in several of the IIHS tests of passenger vans).

The upward motion of the steering column often coincides with the forward and downwards motion of the occupant's head. Where no airbag is fitted this can cause an increase in the severity of the head strike. In one case, this effect contributed to a head deceleration of 250g - one of the highest ever recorded.

In the absence of an airbag, steering wheel hub design plays an important role in reducing head injuries. Considerable research has been undertaken into effective, energy-absorbing hub designs but these do not appear to have been put into production. In some cases the hub cover has flown off just before the head impact, exposing the head to metal components.

#### Sideways movement of the steering wheel

In several offset crash tests the driver dummy rolled off the outboard side of the airbag. Although some outboard motion of the dummy can be expected due to the non-symmetrical crash forces, in most of these cases it is likely that the steering wheel had moved inboard, relative to the driver's seat. One possible factor is that components in the engine bay push the steering column to one side, causing it to pivot about its mounting points. Another possible factor can be gauged from an overhead view at the height of the crash (figures 1 & 4). In many cases there is a substantial angular difference between the front part of the vehicle, containing the dash and steering column, and the rear part containing the passenger compartment - a "jack-knife" effect. The steering wheel therefore moves inboard, relative to the passenger compartment



**Figure 4. Diagram showing possible relative movement of steering wheel**

This effect usually results from excessive deformation in the region of the a-pillar on the driver's side. Rupture of the join between the dash and the a-pillar, and collapse of the door and door sill can also contribute to this problem.

#### Seat belt upper anchorages

Adjustable upper seat belt anchorages improve the fit of the seat belt. However, some designs deform under the severe loads of the crash test and allow additional forward movement of the occupants.

With the trend towards b-pillars which curve substantially inwards between the door sill and the roof there is another source of seat belt "slack". The webbing follows the curved path between the retractor unit and the D-ring and is usually held in place by the trim. During the crash the plastic trim can give way due to tensile forces in the webbing, which then straightens and feeds through the D-ring.

#### CONCLUSIONS

The 64km/h offset crash test places severe demands on the structure of the vehicle. Some vehicles perform exceptionally well during this crash test but many exhibit excessive structural collapse and other undesirable characteristics. The better designs appear to have the following structural features:

- a front structure which absorbs crash energy through controlled deformation and avoids load concentrations on the impacted object,
- structural components which bridge the front footwell area so that compression forces are transmitted directly between the front and rear of the vehicle, resulting in minimal footwell deformation,
- structural components which channel crash forces into the a-pillars, side doors and door sills rather than into the firewall area,
- the join between the top of the a-pillar and the roof is smooth and strong so that upwards buckling of the roof is resisted,
- side doors and door sills which offer resistance to longitudinal compression forces (measures to improve side impact protection appear to have assisted in this regard),
- a steering column designed and mounted to minimise the amount of rearward and upward movement at the height of the crash,

It is evident that these issues are now being taken into account during the early stages of vehicle design. Powerful Computer Aided Engineering (CAE) packages are now able to determine vehicle structural deformation and occupant kinematics during a variety of crash situations, including a simulated offset crash test (Loo and Brandini 1998).

Recent research in Australia indicates that the better designs can provide good protection for their occupants, while having low aggressivity towards the occupants of other vehicles.

## ACKNOWLEDGMENTS

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# OPTIMIZED RESTRAINT SYSTEMS FOR REAR SEAT PASSENGERS

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## ABSTRACT

Restraint systems for front seats have experienced continual improvement in recent years, in particular through the introduction of airbags. The standard for rear seats, however, is still the conventional three-point belt on outer seats and the lap belt for the middle seat position. As using airbags in rear seats is very problematic, the feasibility and protective effect will be examined of a belt system equipped with a belt pretensioner and a load limiter. To do so, first the marginal conditions constituted by legislation, findings from accident investigations, and seat position and belt geometry in rear seats will all be discussed in detail. Results from sled testing and MADYMO simulations allow the following to be said: Optimized belt systems very much reduce thorax loading, the largest effect for chest deflection coming from the load limiter, but for V\*C, on the other hand, from the pretensioner. It emerges that a vehicle crash pulse that is 30% harder with an optimized belt system produces lower thorax loading values for rear seat occupants than a corresponding "softer" pulse with a conventional three-point belt.

## 1. INTRODUCTION

The restraint systems on the front seats of automobiles have been continuously improved in recent years. Thus the best restraint systems today consist of a safety belt with a pretensioner and load limiter, and an airbag. In rear seats, however, the standard is an automatic three-point belt for the outer seats and a static lap belt for the middle seat. Only very few models have a three-point belt on the middle seat and/or a belt system with pretensioner.

Due to the forthcoming introduction of the 40%-ODB crash test as a prerequisite for type approval of automobiles in Europe, and an improvement in vehicle structure for this test, the crumple zones of cars – especially small cars – are becoming stiffer. This can be seen especially in crash tests according to the US-

regulation FMVSS 208 against a rigid barrier with 100% overlap. With vehicle deceleration like this, the dummy loading on rear seats can exceed the respective acceptance levels. It is therefore necessary for the restraint system to be adapted to such vehicle deceleration.

Introducing an airbag also for rear-seat passengers, however, appears problematic. For one thing, there are hardly any suitable mounting locations available, and for another, the out-of-position problems in rear seats would be much greater than in the front passenger seat, also and especially because children are usually transported in the rear seat.

This examination is to show what additional protective effect an improved belt system alone can have. This improvement can be broken down into two stages:

- 1) Belt-pretensioning, which starts within the first milliseconds of an impact, thus creating the optimal preconditions for the restraint system to have its effect,
- 2) Load-limiting, which, while the occupant is being shifted forward, limits the belt forces affecting the occupant and makes the best possible use of the available interior space to decelerate the occupant.

In the following, a survey will first be given of the marginal conditions in which the optimization can take place. To do so, the legislative situation will be described first and the occurrence of accidents with rear-seat occupants explained. A discussion then follows of the special circumstances for rear-seat passengers with regard to seat position and belt geometry. Marginal conditions for optimizing belt systems in rear seats can be derived from these explanations. The improvement possible in the occupant loading values is estimated using sled tests. A MADYMO model was prepared to determine the parameters influencing the dummy loading.



## 2. LEGISLATION

The ECE-R 16, or the corresponding EC Directive 77/541 form the legal basis for type approval of safety belts in Europe. In the ECE-R 16, the tests are listed that a safety belt has to pass through to be approved, or which must be carried out along with production to maintain licensing. Two kinds of testing can be distinguished:

1. Laboratory testing
2. Dynamic sled testing

1. The laboratory tests include testing of sensor systems for locking behavior, measuring of the belt's retracting force, opening force of the buckle, environment-simulation and durability testing, as well as quasi-static breaking load testing of buckles, belts and retractors.

2. A dynamic sled test is to simulate the strength of the belt system in a head-on collision. This is done using a test sled with a steel seat, on which a 75-kg standardized manikin sits, which in its dimensions is supposed to represent a 50-percentile man. The standardized manikin is buckled up with the belt system to be tested with reference to its H-point in the vehicle geometry. The belt system is tested in new condition and after environment-simulation and durability testing. The test sled is accelerated to 50 km/h and exposed to a nearly rectangular deceleration pulse of 26 - 32 g. When this is done, the test manikin may shift forward in the pelvic area between 80 and 200 mm, and in the chest area between 100 and 300 mm; for pretensioner systems, the lower limits are reduced by one half. The belt system must not suffer any damage during the testing.

The ECE-R 16 therefore describes a method for testing belt systems that originates from a time when passive vehicle safety in Europe was still in its infancy. The lower limit of the forward displacement is supposed to assure that the belt system assumes the manikin's energy, without allowing great belt forces to occur; limiting the value upwardly is supposed to prevent the chest and head from coming into contact with any parts of the vehicle in a real accident at a high impact speed. Biomechanical response values, however, were not determined; the manikin is not designed for this purpose.

When optimizing safety belts, the forward displacement of the chest being limited to 300 mm can be a great restriction in the selection of the load-limiter

level most favorable for the occupant. The ECE-R 16 does in fact, under certain marginal conditions, allow for the 300 mm to be exceeded, but these exemptions can only be used for front seats. The relevant regulation for the USA, however, the FMVSS 209, generally allows greater forward displacement of chest.

## 3. ACCIDENT INVESTIGATIONS

There are numerous accident studies that supply evidence for the effectiveness of safety belts in rear seats /1/, but only few that describe the types of injuries to occupants protected by safety belts. The following account is based on an investigation carried out in Great Britain /2/. The study covers accidents that were recorded between 1992 and 1995.

Table 1 shows an overview about injuries and severity of injuries to individual parts of the body. The study included occupants of head-on collisions, roll-over accidents, and in side impacts on the side away from impact. In comparison with the front seat, the severity of injury in the rear seat is much less. Thus in the collective accidents, injuries were suffered by 41.5% of the occupants in the front seats, but only by 23.8% of the occupants in the rear seats.

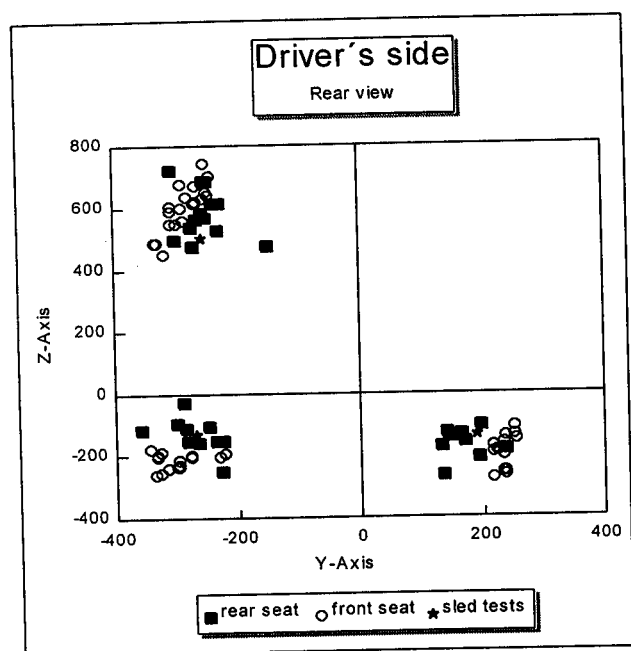
There is a greater probability of abdominal injuries in the rear seats that is very obvious. The belt can be established as the cause of these injuries for 85% of the MAIS 1 injuries and 60% of the MAIS 2+ injuries, allowing one to infer submarining. In addition to arm injuries, which are only classified as MAIS 1, thorax injuries occur most frequently. In these cases, too, the safety belt is considered to be responsible. Among the collective of occupants who had not been wearing a safety belt, the frequency and severity of injuries was higher, as expected. The study estimates that safety belts reduce the risky of injury in rear seats by 40%.

	Rear seat (N = 126)		Front seat (N = 755)	
	%MAIS 1+	%MAIS 2+	%MAIS 1+	%MAIS 2+
Head	3,2	0,8	7,2	2,5
Face	-	-	0,8	-
Neck	0,8	-	2,4	0,9
Arms	6,3	-	8,3	1,7
Thorax	6,3	1,6	10,9	3,8
Abdomen	3,2	1,6	2,1	1,2
Spine	0,8	-	2,8	0,5
Legs	3,2	2,4	7,0	2,8
Sum	23,8	6,4	41,5	13,4

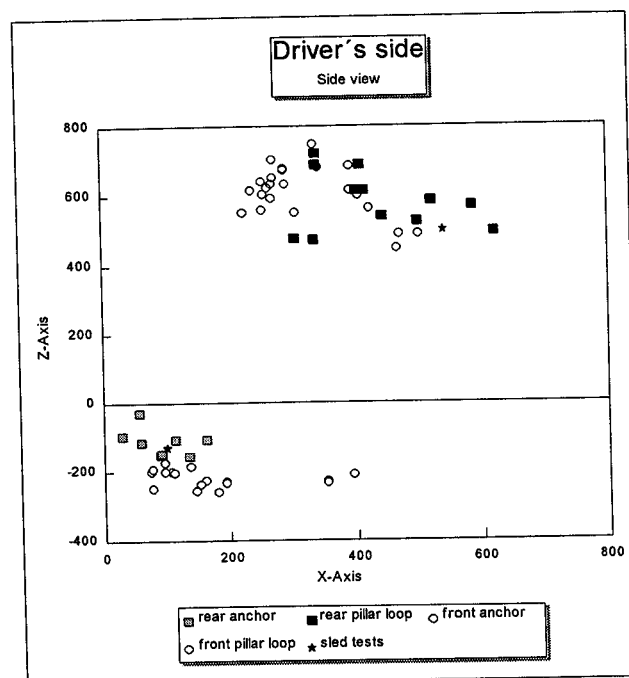
Table 1: Injury severity degrees MAIS 1 or MAIS 2 or more severe for individual parts of the body of automobile occupants protected by safety belts /2/.

#### 4. SEAT POSITION AND BELT GEOMETRY IN REAR SEATS

The belt geometry in rear seats is many times less favorable than in front seats; cf. Figures 1 and 2. This is due on the one hand to vehicle geometry, which does not permit optimal belt-anchoring points – the rear wheel house, for example, restricts the possibilities of fastening the anchor fitting. On the other hand, the rear seat running all the way through results in restrictions in fastening buckles. The seat position of the occupant in the rear seat is also different from in the front seat. Due to the restricted foot space extending to the front seat, the knees bend further causing the pelvis to tilt further backwards. The geometry of belts and the seat position result in the angle between the lap belt and the pelvis normal becoming comparatively small. As a consequence, the risk in a head-on collision of the lap belt slipping over the wings of ilium is evident, i.e., submarining can occur /3/. The upper fastening point of the shoulder belt, which has frequently been positioned far to the rear (cf. Fig 2), also promotes submarining.



**Figure 1:** Position of the belt-anchoring points of various cars, measuring from the H-point of the dummy, in the direction of traffic. Also shown are the anchoring points as they are used in the testing in Section 7.



**Figure 2:** Position of the belt-anchoring points of various cars, measuring from the H-point of the dummy, in the direction of traffic. Also shown are the anchoring points as they are used in the testing in Section 7.

Another point requiring special attention is the back-rest of the front seat. It restricts the room for movement available in frontal collision. The back-rest itself, however, also moves forward during an impact, increasing the room for movement for a certain time window.

#### 5. BELT PRETENSIONING AND LOAD LIMITING

A large amount of slack in the belt system results in a worsening of the occupant loading values during a head-on collision and can promote submarining. Thus 80% of car drivers' belt slack is between 40 and 90 mm in summer and between 40 and 120 mm in winter /4/. Similar belt slackness rates can be expected in rear seats. The pretensioning system is meant to pull the slack out before the shift forward caused by impact has even begun. The belt system is as it were put in the best possible starting condition during the first milliseconds of an accident. In principle the belt system can be tightened at all of its fastening points on the vehicle. The common methods used today are the buckle pretensioner and the retractor pretensioner. With the former the buckle is

pulled down approx. 60 to 80 mm, with the latter the belt roller is wound. Whereas mechanical pretensioner systems were frequently used in the beginning, new vehicles today are usually equipped with pyrotechnically operated systems.

The force limitation in a three-point belt is supposed to limit the belt forces and thus in particular keep the thorax loading values down. Load limiters were used in mass production as early as the beginning of the 70's – back then of course without airbags. Accident analyses substantiate their use /5/. Today load limiters are mostly used in combination with an airbag for optimal performance of the total restraint system.

## 6. MARGINAL CONDITIONS IN OPTIMIZING THE RESTRAINT SYSTEM FOR REAR SEATS

The following marginal conditions in optimizing the rear-seat belt system can be derived from the preceding explanations:

- 1) Owing to belt geometry and seat position, a tendency to submarining occurs, which must not be reinforced through pretensioning and load limiting but rather ideally should even be reduced.
- 2) The load limiting has to be designed such that the free space available to the occupant, which increases dynamically through the back-rest moving forward, is optimally exploited without injury-relevant contact to the head coming about.
- 3) The belt system must qualify for type approval in accordance with ECE-R 16. This means that in the relevant sled testing in accordance with ECE-R 16, the standardized manikin must not move forward at chest height any further than 300 mm.
- 4) The restraint system must be optimized with regard to a chest loading criterion, ideally the viscous criterion  $V^*C$ , because it is evident from the accident analyses that thorax injuries are the ones that play the decisive roll.

## 7. SLED TESTS AND RESULTS

A series of sled tests were carried out to estimate the expected reduction in dummy loading values through an optimized belt system. To do so, a belt geometry and seat position were selected that in our experience are typical (cf. Figs. 1,2 & 6). A Hybrid-III-50-percentile man was used as the dummy. A relatively stiff crash

pulse was deliberately selected (peak deceleration of 33g, cf. Fig. 3), to allow for the fact that modern vehicles are becoming more stiff. The following tests were carried out:

1. Conventional belt system without pretensioner and load limiter,
2. Belt system only with retractor pretensioner, without load limiter,
3. Belt system with retractor pretensioner and load limiter.

A load limiter level of 5.5 kN was selected first because with such a system the ECE-R 16 requirement for maximum chest forward displacement of 300 mm can be met. In all the tests, after approx. 60 ms, the seat upholstery bottomed out, which resulted in strong vertical deceleration and influenced the dummy data measured. Such behavior can also be observed in real crash tests in which the dummy pelvis pushes through against the underseat panel.

Table 2 gives an overview about the test results. The data measured, which is against a gray background, have their maximum during the time interval of the pushing through and cannot be compared directly like this. A clear reduction can be seen in chest loading with a pretensioner and especially with a pretensioner and a load limiter. This appears especially in the values measured for  $V^*C$  and chest deflection, which are not influenced by the seat upholstery being pushed through (Fig. 4).  $V^*C$  in test 3 is around 70% lower in comparison with reference test 1, and the chest deflection by 40%. A possible reduction in the resulting chest deceleration by 20% can be estimated from the chest deceleration in direction x. A clear drop in head and neck loading can also be seen. As no contact to the head took place, in this case the HIC can only be considered as a reference value.

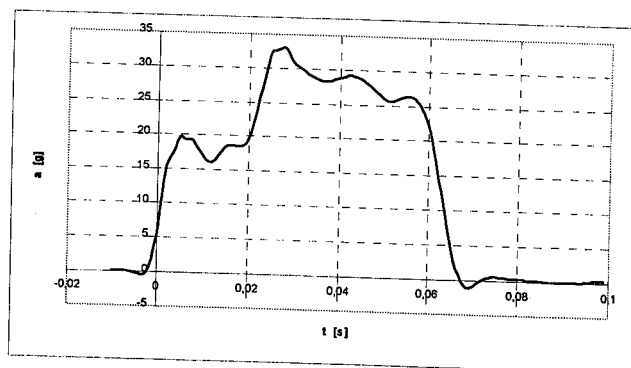
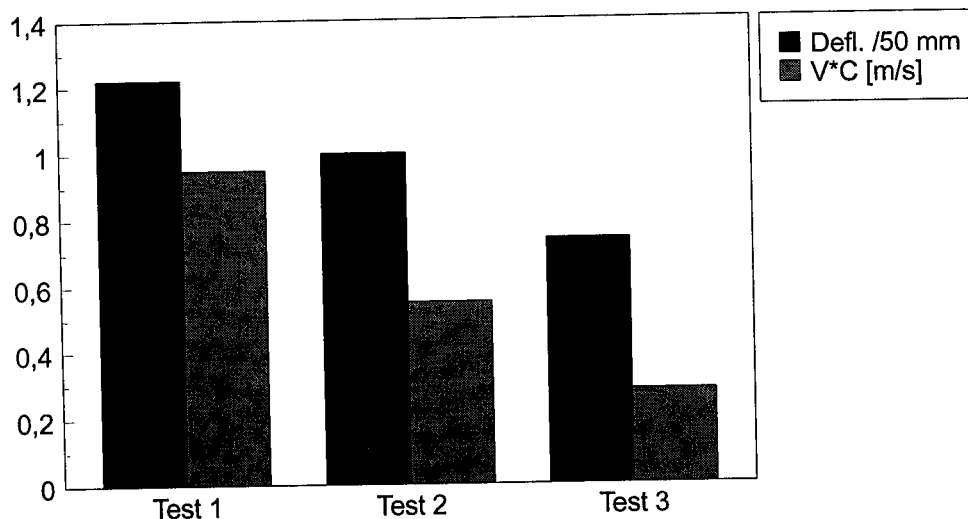


Figure 3: „Stiff“ crash pulse for sled tests and MADYMO simulation

		Test		
		1	2	3
Head	HIC36	888	663	458
	a 3ms [g]	73.0	67.3	57.3
Neck	Fx [kN]	1.64	1.53	1.14
	Fz [kN]	2.75	2.49	2.24
	Extension [Nm]	66	18	73
	Flexion [Nm]	152	163	101
Thorax	Defl. [mm]	61.0	49.8	36.9
	a 3ms [g]	60.8	54.6	56.7
	a max x-Dir. [g]	60.5	54.8	47.6
	V*C [m/s] *)	0.95	0.55	0.28
Pelvis	a 3ms [g]	71.7	77.3	91.8
	a max x-Dir. [g]	54.2	52.2	44.9
Belt Force	Shoulder [kN]	10.8	10.0	5.9
	Anchor Fitting [kN]	11.4	11.1	10.4

\*) calculated in accordance with SAE J 1727

**Table 2:** Test results of the sled tests.



**Figure 4:** Sled tests 1-3, V\*C and chest deflection as a function of the belt system

## 8. THE DEVELOPMENT OF A MADYMO MODEL

Analogously to the sled tests, a MADYMO model was set up and validated. The geometry of the simulation model matched the structure of the sled tests. The model was correlated using test no. 2 (with pretensioner, without load limiter) and checked on tests 1 and 3.

Good agreement appears both in the kinematics and in the time history of acceleration, especially in the chest and pelvic areas (Figure 5). As a result, the simulation

model describes reality very well and serves as a basis for the following parameter study.

It was not, however, possible to reproduce in the MADYMO model so markedly the strong snapping over of the neck (approx. 90° relative to the upper part of the body). One possible cause for this might be the nape modeling of the TNO HIII dummy model possibly being too coarse for such extreme head/neck movements. Since the study concentrates primarily on the chest area, this was accepted in this case.

A further point is the difference in the  $V \cdot C$  values between simulation and testing. The  $V \cdot C$  value is calculated from the product of chest deflection and the deflection speed in relation to a reference value. In the test, the deflection speed is derived from the filtered signal from the chest potentiometer. This signal is by its nature not a curve with a smooth shape, and so an oscillating signal results for the speed derived from this. This oscillation also turns up again in the time history of the  $V \cdot C$ . Furthermore, the signal is very dependent upon the filtering method selected - e.g. SAE J1727 and EC Directive 96/79/EC prescribes different methods. The testing therefore yields a maximum  $V \cdot C$  because of a vibration peak and not from the global shape of the curve. This behavior is not to be seen in the simulation because there the signals are not provided with metrological static. The course of the  $V \cdot C$  is

"smoother" on the whole with a lower maximum value resulting from this. This is to be taken into account when one makes a comparative examination.

Furthermore, an attempt was made to obtain an indicator for submarining with the simulation model. In the parameter study carried out this was done by looking at the time history of the belt/pelvis angle, although the relatively simple belt modeling in the simulation model used only allows a relative belt/pelvis motion in the direction of the belt and not perpendicularly; i.e., true slippage of the belt over the pelvic pan is not possible in this case. Nevertheless, using a definition of relevant limiting angles (cf. /3/), it should, with comparatively little modeling expenditures, still be possible to make a statement about possible submarining. In no cases must submarining be allowed such that a yes/no statement is sufficient in this case.

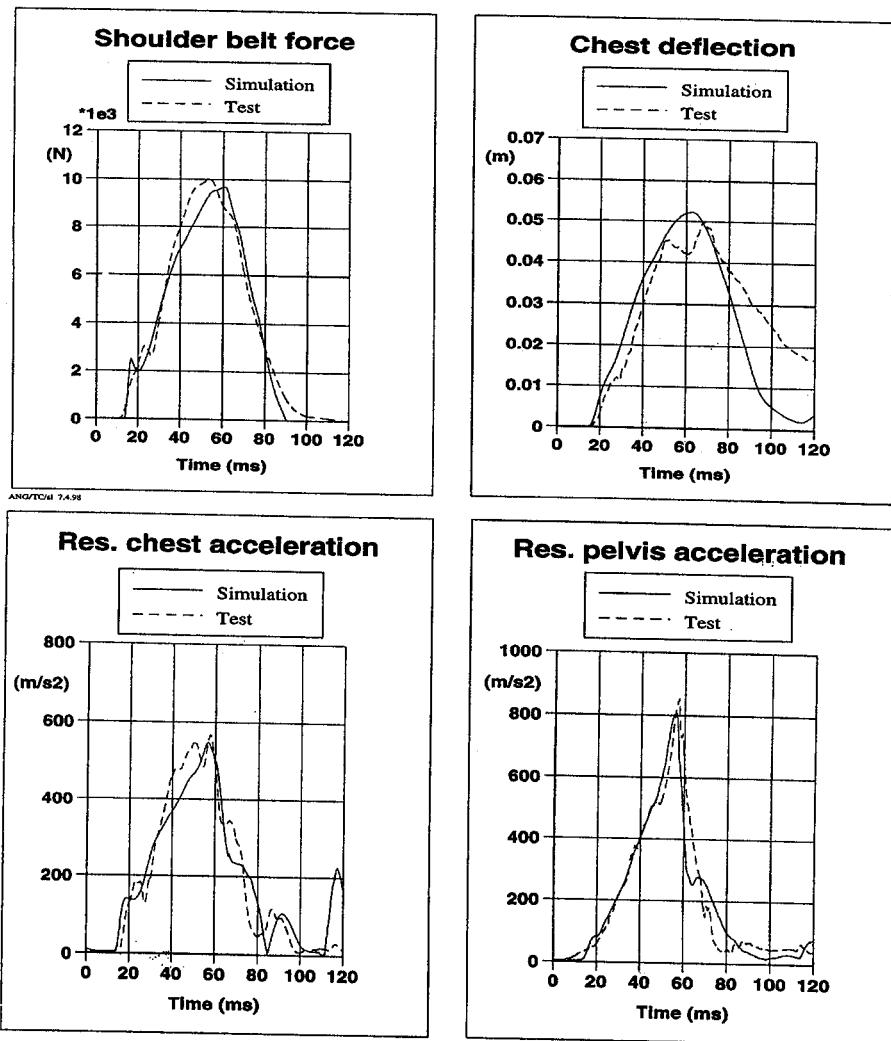
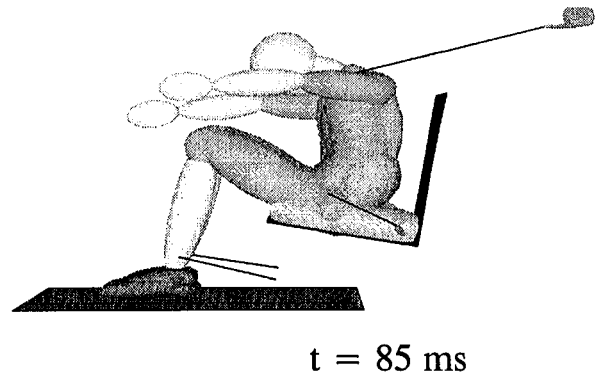
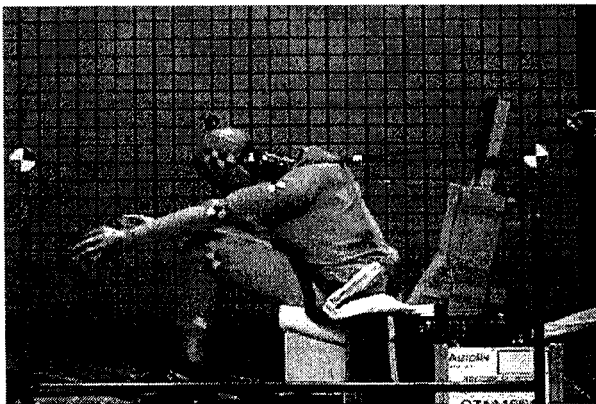
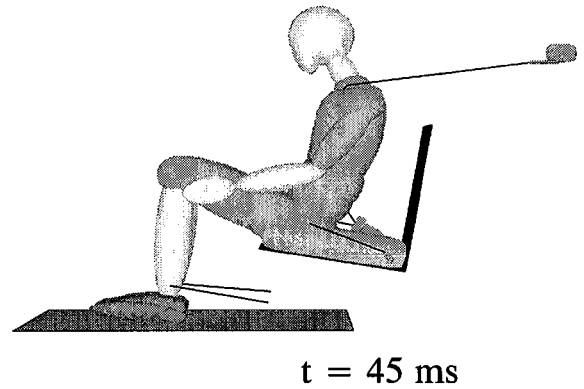
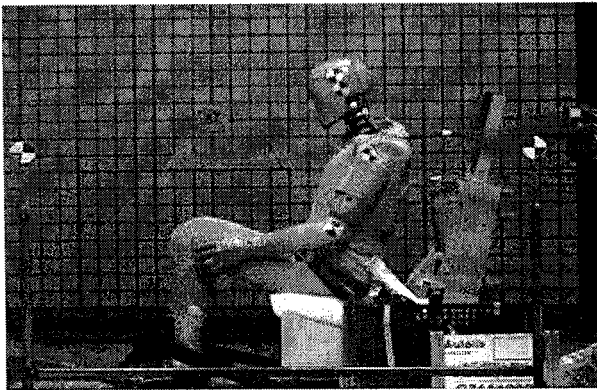
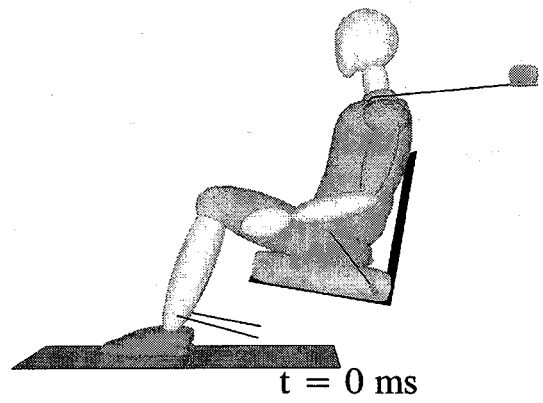


Figure 5: Results of the MADYMO simulation in comparison with the sled test.



**Picture 6: Sled test No. 2 in comparison with MADYMO-Simulation**

## 9. DETERMINING THE INFLUENCING PARAMETERS ON THE DUMMY LOADING

To determine the influence of individual parameters on dummy loading, three series of MADYMO simulations were carried out and evaluated for the effects of the individual parameters. In doing so, special attention is given to chest deflection and V\*C. The testing was carried out separately for the three possible pretensioner systems - retractor, buckle and anchor-fitting pretensioners. To keep the simulation expenditures as low as possible, the influences were examined in a test matrix following the partially factored plan L16 2<sup>8-4</sup>. This makes it possible to separate the individual influences from one another; only 16 simulations per type of pretensioner were necessary. Table 3 gives an overview about the individual parameter settings. The most favorable setting in each case is against a gray background. The corresponding settings for the sled tests are given as a comparison.

The variation of the belt anchoring points (parameters A and B) is supposed to cover the area possible in the vehicle (cf. Figures 1 and 2). The belt slackness approximately represents an average value of real belt slackness in summer and winter, cf. Section 5. The two stages of the foot position are supposed to represent the positions possible for the lower extremities with the front seat pushed forward or to the rear respectively. The range of variation of the angle of the seat ramp is supposed to cover a wide range of possible settings. The load limiter level was first selected according to the marginal conditions given (cf. Section 7). The variation of the vehicle pulse is supposed to make it possible to determine the influence of "stiff" and "soft" vehicles.

Table 4 and Fig. 7 give an overview about the effects of the individual parameters on chest deflection and viscous criterion. Interactions between two parameters only occur starting with the sixth position for chest deflection and starting from the fourth position for V\*C and are not considered in the following.

The following picture results as far as chest deflection goes: A substantial reduction of 10 mm is caused by the force limitation, followed in second place by the vehicle pulse at 6 mm. The pretensioning contributes with approx. 5 mm and is in third place with retractors and anchor-fitting pretensioners.

For V\*C, tightening for retractor and anchor-fitting pretensioners has the greatest influence; for buckle pretensioners, the belt slack that follows in second place for the other pretensioners. For buckle pretensioners it

has to be mentioned that their tightening distance was limited to 60 mm in this study. If correspondingly longer distances were provided, it would definitely be possible to reduce the influence of belt slack in such cases. Vehicle pulse follows in third place for all types of pretensioners. Load limitation only follows starting from the fifth position. This can be explained in that V\*C already assumes its maximum value before the force limitation comes into effect.

The simulations clearly shows that the influence of the characteristics of a modern belt system, i.e., pretensioning and force limiting, is greater on the chest loading values than the influence of a 30% stiffer crash pulse.

A goal was set in the beginning to obtain a reliable quantitative statement about submarining also with a simple MADYMO belt model by looking at the belt/pelvis angle, but during the course of the study, it turned out that this could not be achieved. This applies in particular to the parameters of tightening and belt slack, which change the belt geometry in the pelvis area from the very beginning. The following qualitative statements about these influences, however, can be made:

- *Rear, upper fastening point of shoulder belt:*

This anchoring point should be as far forward as possible toward occupant shoulder. An anchoring point far in the rear promotes submarining.

- *Anchor fitting, buckle attachment:*

Fastening points should be placed as far down as possible to avoid submarining.

- *Angle of seat ramp:*

A steeper seat ramp has an effect against submarining.

- *Load limiting:*

Force limitation in the retractor reduces the danger of submarining. The dummy's bending in the pelvic area enables the chest to move forward further and this a more favorable course of the belt in the pelvic area.

Caution must be exercised in interpreting the influences of the belt geometry (parameters A and B) on V\*C and chest deflection. Low chest loads are obtained especially with the belt geometries that produce the greatest danger of submarining. A pelvis that is shifting forward sharply and turning in relieves the load on the chest area. But since submarining must definitively not be allowed, these parameter settings must be classified as less favorable on the whole (c.f. Table 3).

	Parameter	Stage 1	Stage 2	Sled tests
A	Anchor fitting, buckle (from H-point) x,z [mm]	100/-180 low	100/-80 *) high	100/-130 medium
B	Upper fastening point of shoulder belt (from H-point) x,z [mm]	350/700 to front, high	540/500 *) rearward, low	540/500 rearward, low
C	Belt slack (each 50 mm pelvis and thorax)	without	yes	without
D	Foot position (from H-point) x [mm]	-470 to front	-300 rearward	-470 to front
E	Seat ramp	5° small	15° big	10° medium
F	Load limiter	5.5 kN	without	5.5 kN, without
G	Crash pulse[g]	33 „stiff“	25 „soft“	33 „stiff“
H	Pretensioner	yes	no	yes/no

**Table 3:** Selection of the parameters for MADYMO simulation; against gray background the most favorable parameter settings for thorax loading.

\*) This setting is in fact the best one for thorax loading, but extremely unfavorable for submarining, cf. text.

	Pretensioner  Parameter	Retractor		Buckle		Anchor Fitting	
		Defl. [mm]	V*C [m/s]	Defl. [mm]	V*C [m/s]	Defl. [mm]	V*C [m/s]
A	Anchor fitting, buckle	3.47	0.020	3.18	0.020	3.36	0.027
B	Fastening shoulder belt	3.89	0.051	4.32	0.060	4.05	0.051
C	Belt slack	4.52	0.109	5.13	0.141	4.53	0.109
D	Foot position	2.67	0.029	2.48	0.022	2.49	0.023
E	Seat ramp	2.70	0.023	3.13	0.020	2.82	0.019
F	Load limiter	9.96	0.025	10.16	0.027	10.41	0.027
G	Crash pulse	6.57	0.103	6.46	0.099	6.47	0.095
H	Pretensioner	5.24	0.159	4.13	0.126	5.08	0.143

**Table 4:** The parameters' influence on chest deflection and viscous criterion, each showing the effect of the optimal setting in accordance with Table 4; the three main influencing quantities against a gray background.

## 10. THE LOAD LIMITER LEVEL AND THE DUMMY'S FORWARD SHIFT

As shown in the previous section, the force limiter provides the greatest contribution to reducing chest deflection. In another simulation series, the influence of the force limiter level on chest loading was therefore systematically investigated, the geometry having been selected corresponding to the sled tests with stiff crash pulse (Fig. 3), but with a seat ramp angle at 15° to avoid submarining. The results are listed in Figure 8 as a function of the maximum shift forward determined in the head's center of gravity. One first sees a clear reduction

in chest deflection with a reduction of the force limiter level from 10 kN to 7 kN without forward shift increasing a great deal. With a further reduction of the force level, a clear increase in the head's forward shift results, which, however, at 5 kN is still less than 550 mm. With regard to the reduction mentioned in the previous section of the tendency toward submarining through a low load limiter level, the space available in a vehicle should definitely be taken advantage of and a force level selected below 6 kN if possible.

In the course of the V\*C it can be seen that no clear reduction occurs until between 4 kN and 5 kN. Since the clearance to the limit value is large in this case,



however, a drop to under 5 kN does not appear necessary. But especially because of the problems dealt with in Section 8 concerning the comparability of the V\*C of real testing and simulation, when optimizing the

belt system for a certain model of vehicle, this should be examined in body-in-white and full-size crash tests.

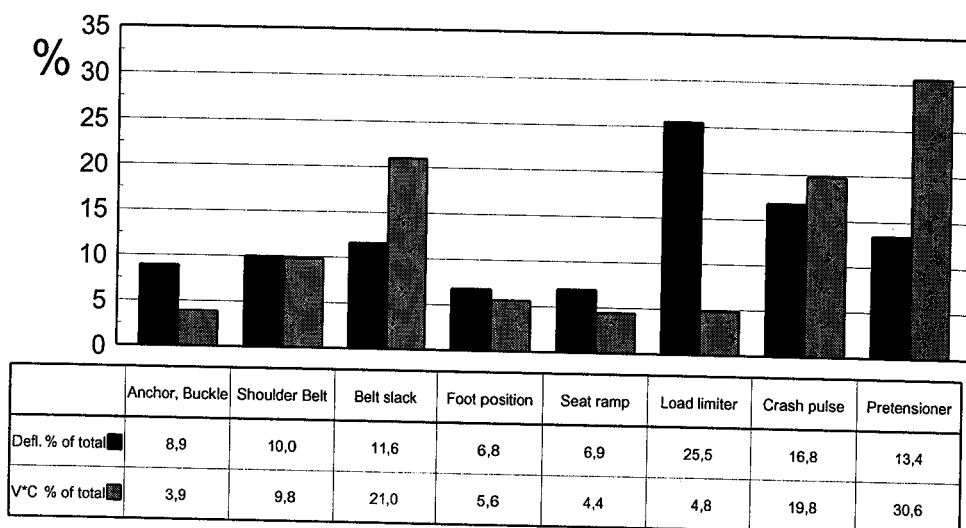


Figure 7: The influence of the parameters on chest deflection and V\*C for retractor pretensioning.

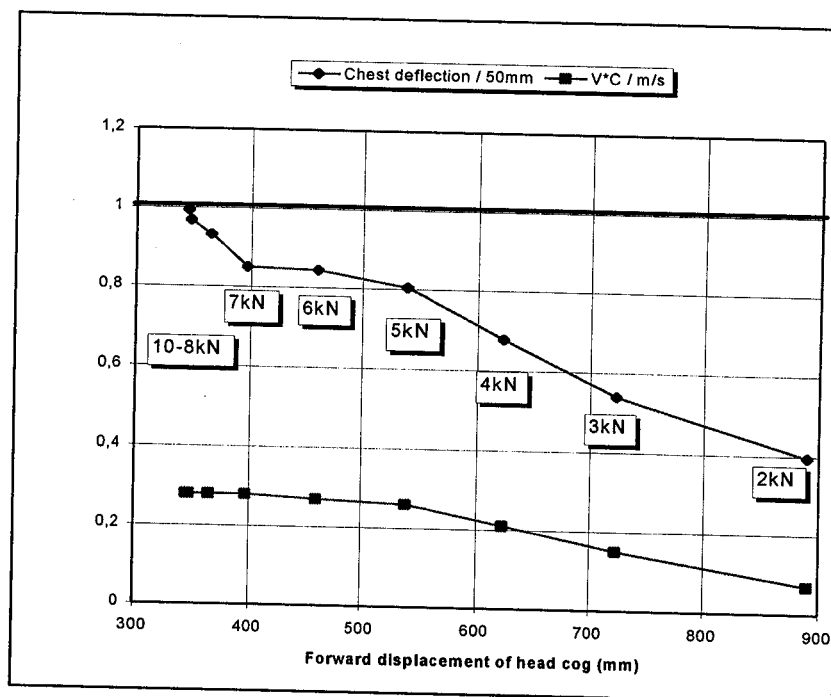


Figure 8: Chest deflection and V\*C as a function of the forward displacement of the head measured in the center of gravity.

## 11. CONCLUSIONS

Accident investigations show that thorax injuries are the predominant type of injury to rear seat occupants. Using sled tests, it has been proven that chest loads in particular can be very much reduced through belt systems with pretensioners and load limiters. There is a validated MADYMO model available with which the quantities influencing the chest loading values have been investigated. It turns out that a 30% stiffer crash pulse with an optimized belt system produces lower thorax load values than a corresponding "softer" pulse with a conventional three-point belt.

The selection of an optimal force limiter level, however, depends in particular on the room to move available for the rear seat passenger in the individual car. The aim of further studies must be to examine the optimal setting also for other types of dummies (i.e., 5% female, 95% male). One must assume and first simulations show that for 95% male at a constant load limiter force level, greater and possibly inadmissible head shifts forward will result. A solution could be to use adaptive force limiters that automatically adjust themselves to the respective occupant /6/.

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# PATTERNS OF ABDOMINAL INJURY IN FRONTAL AUTOMOTIVE CRASHES

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## ABSTRACT

The Hybrid III, which is the only universally used frontal crash anthropomorphic test device, lacks a biofidelic abdomen that can be used for different loading surfaces and loading rates. The Frangible Abdomen, developed by General Motors in 1989, is the only commercially available, dynamically tuned insert. While the Frangible Abdomen has biofidelity under belt loading conditions, it has neither the loading rate sensitivity nor the appropriate mechanical response (biofidelity) for assessing injury from non-belt impacts (e.g., airbags or steering wheels). A loading rate sensitive abdomen that is also capable of assessing injury is currently under development by the General Motors Safety Research Department. In order to develop such a device, it is important to identify the frequency and severity of injury to the various regions and organs in the abdomen to prioritize their instrumentation with the appropriate sensors.

In this study, crash data collected between 1988 and 1994, contained in the database of the National Automotive Sampling System (NASS), were analyzed to identify the frequency and severity of injury to the abdominal organs in frontal crashes. Results are summarized and compared with previously published studies.

## INTRODUCTION

Anthropomorphic Test Devices are used as human surrogates to assess crash injuries. The Frangible Abdomen developed by General Motors in 1989 is the only commercially available, dynamically tuned, biofidelic insert used to assess abdominal injuries. The insert is a crushable Styrofoam<sup>®</sup> designed to be biofidelic under belt loading conditions (~3m/s) (Rouhana 89,90, Schneider 92). Crush of the foam is used as an indicator of submarining and the amount of crush quantifies the injury risk. This design, however, does not prove to be useful in assessing the interaction of the abdomen with the steering wheel, the airbag, or other objects in the vehicle.

There have been a number of attempts to produce an instrumented abdominal insert (Ishiyama 94, Biard 93, Czernakowski 87, Mooney 86, Melvin 86, Maltha 81, and Walfisch 80). But these systems have also only dealt with

the belt interaction. They have used either deflection, force, fluid pressure measurements, or contact switch signals to indicate injury level in the abdomen. There have been many methods proposed to define abdominal injury criteria. However, the most promising criterion is the Viscous Criterion (VC) proposed by General Motors in 1985 (Rouhana 85, 93, Lau 86). VC is the maximum of the velocity multiplied by the normalized compression of the abdomen during the impact  $[(V(t)*C(t))_{max}]$ .

An instrumented, rate-sensitive, reusable abdomen is currently under development by General Motors Safety Research Department. To assess injuries to the abdomen, the location of sensors and parameters to be measured must be defined. This study is a part of that program and was undertaken to set instrumentation priorities by determining the frequency and severity of injury to various organs in the abdomen as suggested by field crash data.

## METHOD

Abdominal injury data from the National Automotive Sampling System (NASS) database was retrieved for the years 1988 to 1994. Data were restricted to passenger cars and light trucks involved in frontal impacts without rolling over (PDOF 10-2 o'clock). Also, data were limited to non-ejected drivers and right front seat passengers (RFP). The weighted frequency for injuries with AIS  $\geq 3$  and the corresponding contact objects were collected.

Unknown variables were ignored, thus the total number of injuries and associated contact points collected do not represent the actual total weighted frequencies. Therefore, relative percentages and not the absolute numbers are the focus of this study. In order to directly associate injuries with contact objects, cases with either unknown injuries or unknown associated contact object were ignored.

## RESULTS

The database was analyzed to provide a comparison to other injuries in frontal crashes. Table 1 shows a comparison of injuries by body region for different AIS levels. The body regions chosen are the head, neck, chest, abdomen, and the femur. As the AIS severity increases, abdominal injuries become more prominent. Abdominal

injuries constituted 8% of all injuries of AIS  $\geq 3$ , 16.5% of all injuries of AIS  $\geq 4$ , and 20.5% of all injuries of AIS  $\geq 5$ . Throughout the figures that follow, a number of abbreviations are used for clarity. Tables 2 and 3 give the key to deciphering those abbreviations for restraint type and associated contact objects, respectively.

**Table 1.**

**A Comparison of Injuries by Body Region for Different AIS Levels. As AIS Level Increases, Abdominal Injuries Become More Prominent**

	AIS $\geq 3$	AIS $\geq 4$	AIS $\geq 5$
Head	27.8%	35.3%	34.1%
Neck	3.4%	1.8%	2.2%
Chest	37.6%	46.3%	43.3%
Abdomen	8.0%	16.5%	20.5%
Femur	23.2%	0.2%	0.0%
Total	100%	~100%	~100%

Table 4 and Figure 1 show the normalized frequency (100% = 83,322) of abdominal injuries reported for drivers and right front seat passengers with different restraint systems. The unbelted driver (59%) followed by the lap/shoulder belted passenger (12%) sustained the highest frequency of abdominal injuries. The liver is the most frequently injured organ (38%), followed by the spleen (23%), the digestive system (17%), the arteries and veins (12%), the respiratory system (4%), the kidney (4%), and the urogenital system (3%).

Table 5 and Figure 2 show the normalized frequency (100% = 78,992) of objects contacted that were associated with abdominal injuries. The highest percentage of abdominal injuries were associated with the steering wheel (68%), then with the belt system (17%), the interior (14%), and the airbag (0.13%). The abdominal injury frequency of the driver and the passenger is similar to that shown in Table 4 and Figure 1; 59% for the unbelted driver and 12 % for the lap/shoulder belted passenger.

**Table 2.**

**Abbreviation Definition for the Driver and Front Seat Passenger with Different Restraint Systems**

	Driver	Front Seat Passenger
Lap belt + Shoulder belt + Airbag	D/LSB	P/LSB
Lap belt + Shoulder belt	D/LS	P/LS
Airbag only	D/B	P/B
Lap belt only	D/L	P/L
Shoulder belt only	D/S	P/S
No restraint	D/	P/

Table 6 and Figure 3 directly relate NASS investigators' estimates of objects contacted with the associated injured organs. The steering wheel is most often associated with liver injuries (34%), and spleen injuries (14%). The seat belt is most often associated with injuries to the digestive system (10%). The airbag is only associated with spleen injuries (0.33%). Other interior objects are mostly associated with spleen injuries (7%), and liver injuries (3%).

Tables 7 to 9, and their corresponding graphic representations shown in Figures 4 to 6, show detailed injury distributions associated with the seat belt, the steering wheel, and the interior, respectively. These tables and graphs show the normalized frequency of associated injuries to abdominal organs as they relate to the driver and the right front seat passenger with different restraint systems.

Table 7 and Figure 4 show that the belt is mostly associated with digestive injuries in lap/shoulder belted passengers (48%). Passengers wearing only shoulder belts show more spleen (11%) injuries than liver (4%) injuries. In contrast, drivers wearing only shoulder belts show no spleen injuries and 3% liver injuries.

Injuries associated with the steering wheel are shown in Table 8 and Figure 5. The data show that the steering wheel is mostly associated with injuries to the unbelted driver (87%) and drivers wearing only shoulder belts (12%). The most prevalent injuries sustained by the unbelted driver are in descending order: liver (39%), spleen (20%), arteries and veins (13%) and the digestive system (8%). Drivers wearing only shoulder belts mostly sustained liver injuries (11%).

Data for airbag associated injuries show that 100% of injuries occurred to the unbelted driver with airbag. Table 9 and Figure 6 present abdominal injuries associated with the vehicle interior. The data show that of those injured by vehicle interior components, 70% were unrestrained passengers. Splenic injuries were most prevalent (49%) followed by the liver (23%).

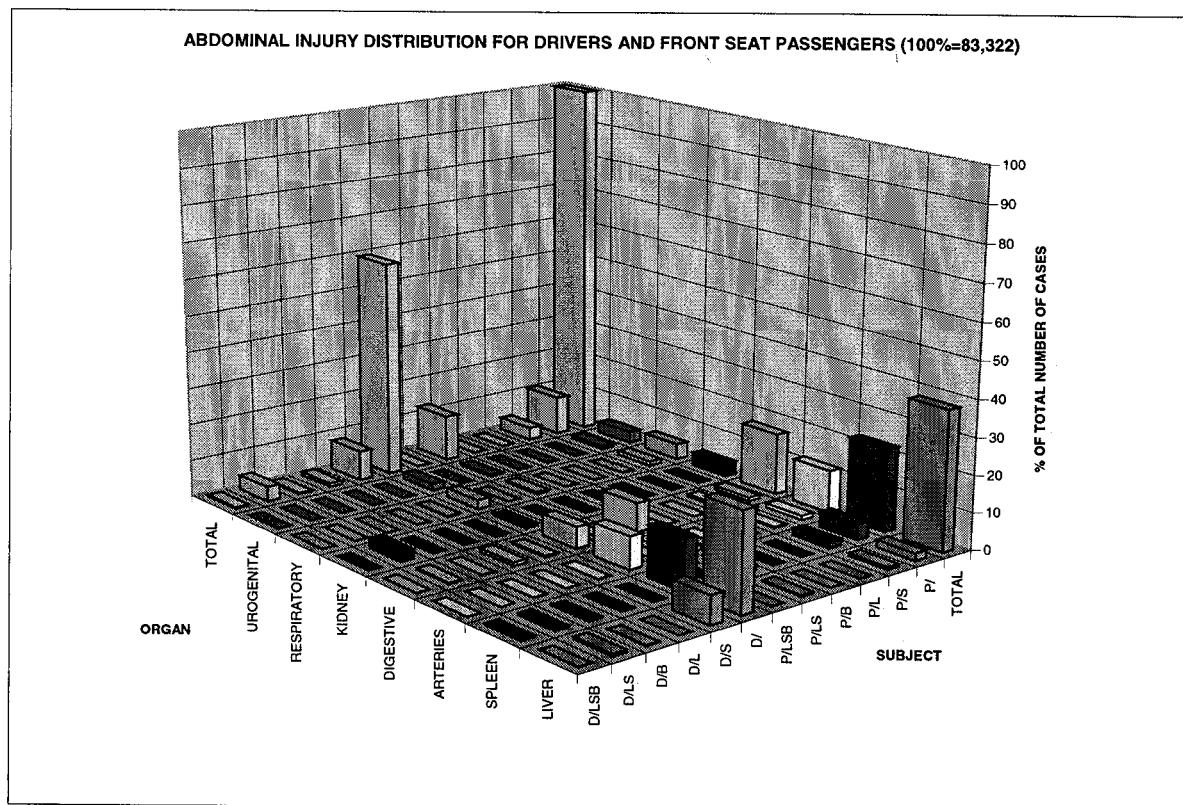
**Table 3.**

**Abbreviation Definition for the Contact Objects Used in this Study**

Label	Object
Belt	Seat belt
SW	Steering wheel
Bag	Airbag
Interior	Windshield, Left IP, Left interior, Left armrest, Other front, Center IP, Shift lever, Right IP, Glove box, Right interior, or Right A-pillar

**Table 4.**  
**Normalized Frequency of Abdominal Injuries for Drivers and Front Seat**  
**Passengers with Different Restraint Systems (100%=83,322)**

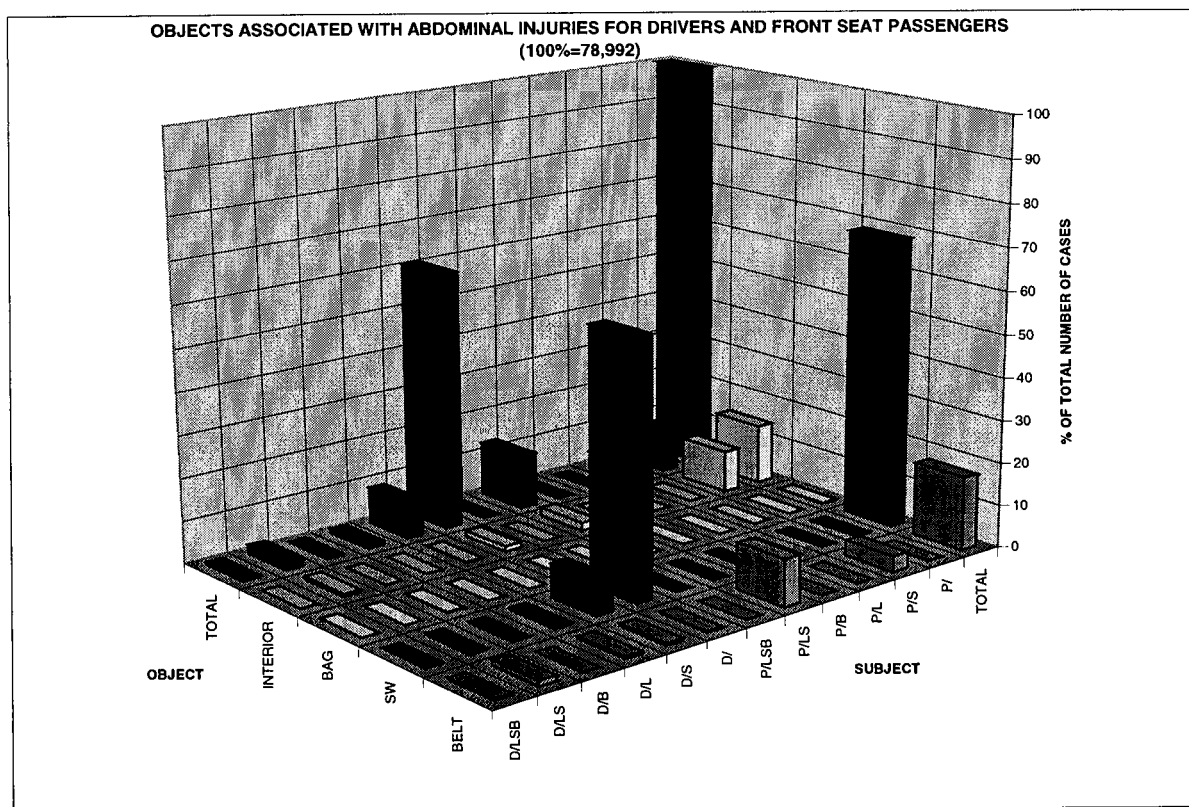
	LIVER	SPLEEN	ARTERIES	DIGESTIVE	KIDNEY	RESPIRATORY	UROGENITAL	TOTAL
D/LSB	0.03%	0.42%	0.00%	0.00%	0.00%	0.00%	0.00%	0.45%
D/LS	0.66%	0.47%	0.01%	0.25%	2.63%	0.00%	0.00%	4.03%
D/B	0.13%	0.18%	0.00%	0.00%	0.00%	0.00%	0.00%	0.31%
D/L	0.00%	0.04%	0.00%	0.94%	0.00%	0.00%	0.00%	0.98%
D/S	7.58%	0.00%	0.00%	0.32%	0.08%	0.17%	0.00%	8.14%
D/	26.32%	13.65%	8.81%	5.82%	0.63%	2.40%	1.84%	59.47%
P/LSB	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
P/LS	0.39%	1.75%	1.34%	7.88%	0.12%	0.52%	0.47%	12.48%
P/B	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
P/L	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
P/S	0.71%	1.81%	0.29%	0.63%	0.00%	0.00%	0.00%	3.44%
P/	2.03%	4.27%	1.20%	0.97%	0.13%	1.23%	0.87%	10.70%
TOTAL	37.85%	22.60%	11.65%	16.81%	3.59%	4.32%	3.17%	100.00%



**Figure 1. Normalized frequency of abdominal injuries for drivers and front seat passengers with different restraint systems.**

**Table 5.**  
**Normalized Frequency of Objects Associated with Abdominal Injuries for Drivers and Front Seat Passengers**  
**with Different Restraint Systems (100%=78,992)**

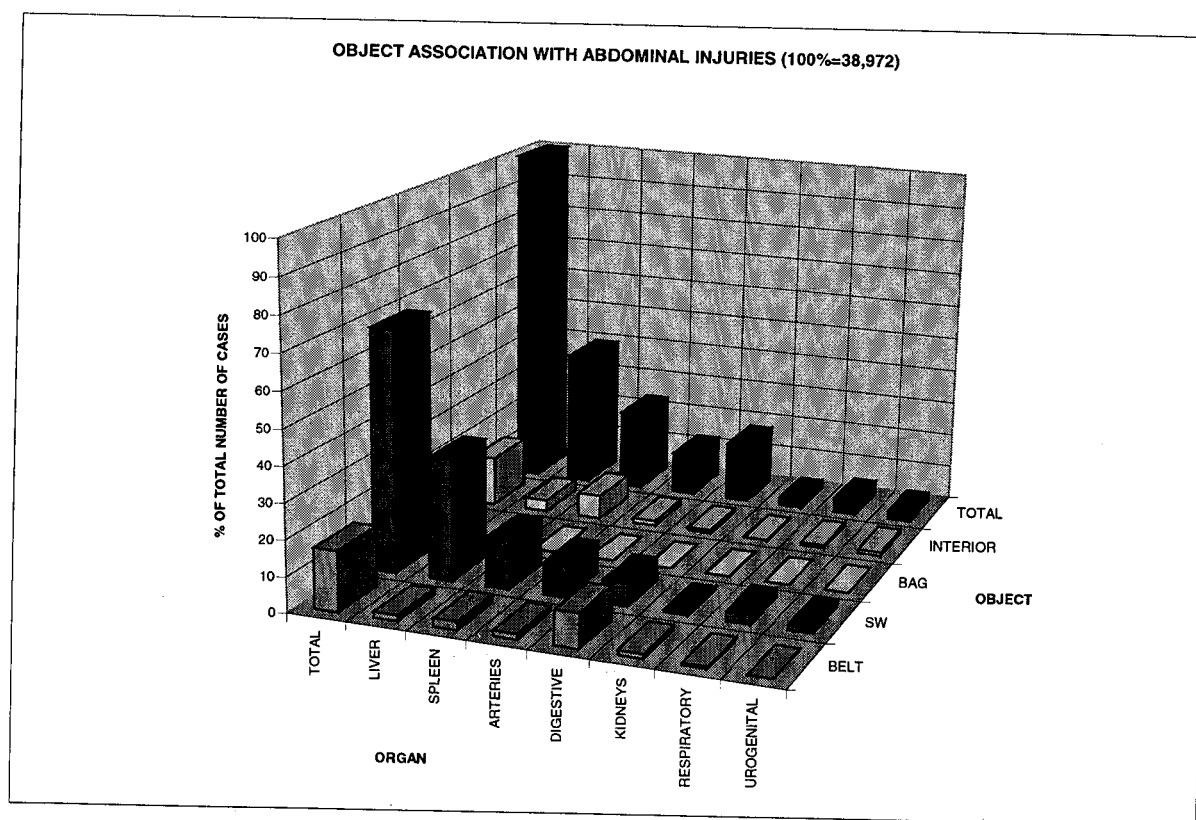
	BELT	SW	BAG	INTERIOR	TOTAL
D/LSB	0.35%	0.06%	0.00%	0.07%	0.48%
D/LS	1.27%	0.27%	0.00%	0.65%	2.19%
D/B	0.00%	0.12%	0.13%	0.08%	0.33%
D/L	0.50%	0.44%	0.00%	0.00%	0.93%
D/S	0.50%	7.91%	0.00%	0.18%	8.59%
D/	0.23%	59.39%	0.00%	1.28%	60.90%
P/LSB	0.00%	0.00%	0.00%	0.00%	0.00%
P/LS	10.85%	0.00%	0.00%	1.98%	12.82%
P/B	0.00%	0.00%	0.00%	0.00%	0.00%
P/L	0.00%	0.00%	0.00%	0.00%	0.00%
P/S	3.63%	0.00%	0.00%	0.00%	3.63%
P/	0.00%	0.18%	0.00%	9.95%	10.13%
<b>TOTAL</b>	<b>17.31%</b>	<b>68.38%</b>	<b>0.13%</b>	<b>14.18%</b>	<b>100.00%</b>



**Figure 2. Normalized frequency of objects associated with abdominal injuries for drivers and front seat passengers with different restraint systems.**

**Table 6.**  
**Contact Object Association with Injured Organs (100%=38,972)**

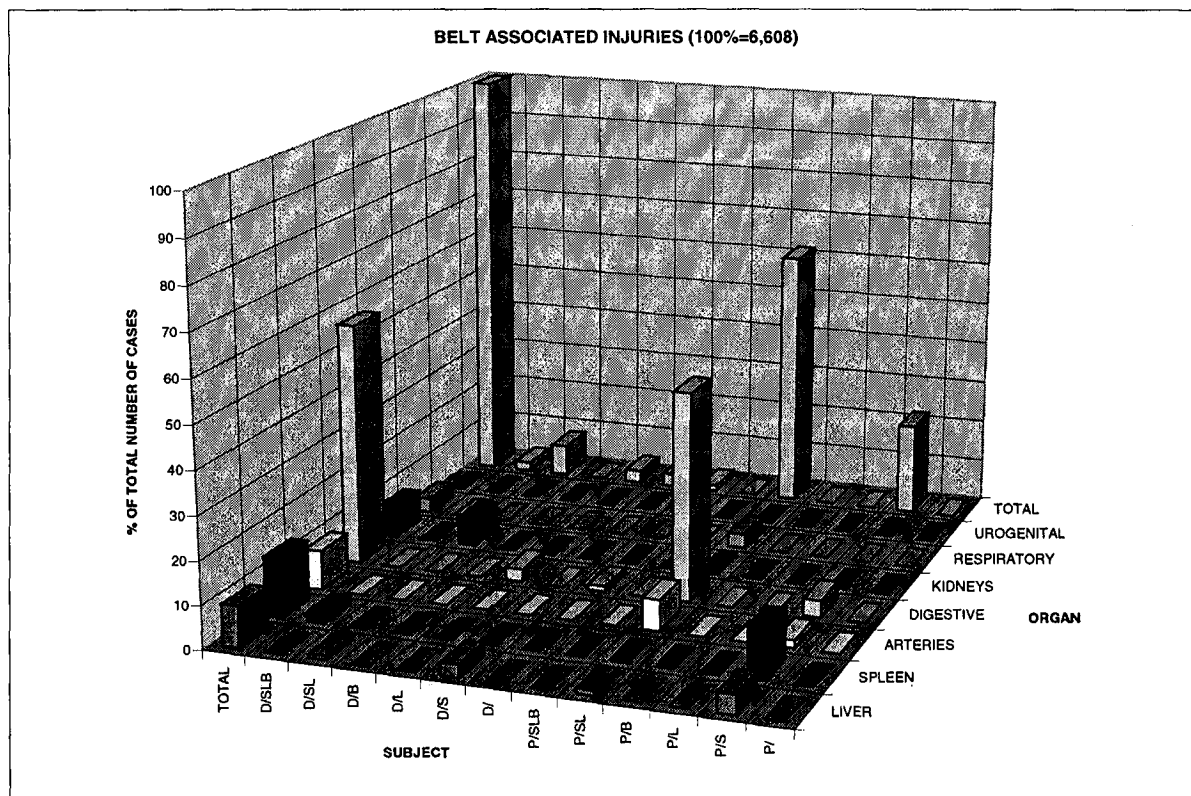
	LIVER	SPLEEN	ARTERIES	DIGESTIVE	KIDNEYS	RESPIRATORY	UROGENITAL	TOTAL
BELT	1.63%	2.34%	1.54%	9.62%	1.26%	0.56%	0.00%	16.95%
SW	34.31%	13.72%	9.07%	6.68%	0.76%	2.69%	1.49%	68.72%
BAG	0.00%	0.13%	0.00%	0.00%	0.00%	0.00%	0.00%	0.13%
INTERIOR	3.26%	6.89%	1.37%	0.84%	0.14%	0.77%	0.93%	14.19%
TOTAL	39.20%	23.08%	11.98%	17.13%	2.17%	4.02%	2.41%	100.00%



**Figure 3. Contact object association with injured organs.**

**Table 7.**  
**Frequency of Abdominal Injuries Associated with the Seat Belt for Drivers and Front Seat Passengers**  
**with Different Restraint Systems (100%=6,608)**

	LIVER	SPLEEN	ARTERIES	DIGESTIVE	KIDNEYS	RESPIRATORY	UROGENITAL	TOTAL
D/LSB	0.00%	2.08%	0.00%	0.00%	0.00%	0.00%	0.00%	2.08%
D/LS	0.87%	0.00%	0.00%	0.00%	6.69%	0.00%	0.00%	7.56%
D/B	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
D/L	0.00%	0.00%	0.00%	2.97%	0.00%	0.00%	0.00%	2.97%
D/S	2.99%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	2.99%
D/	0.00%	0.00%	0.00%	1.35%	0.00%	0.00%	0.00%	1.35%
P/LSB	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
P/LS	1.29%	0.28%	7.29%	48.41%	0.76%	3.31%	0.00%	61.34%
P/B	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
P/L	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
P/S	4.48%	11.42%	1.81%	4.00%	0.00%	0.00%	0.00%	21.71%
P/	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
TOTAL	9.62%	13.78%	9.10%	56.73%	7.46%	3.31%	0.00%	100.00%

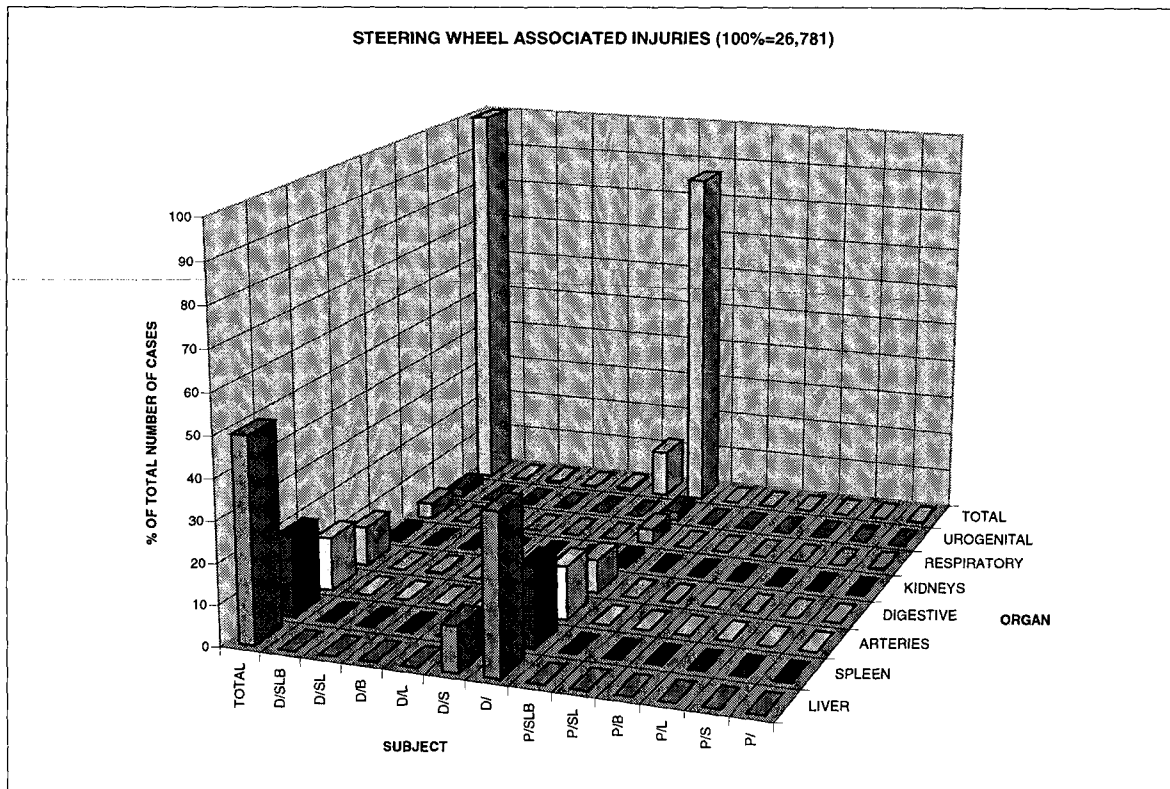


**Figure 4. Frequency of abdominal injuries associated with the seat belt for drivers and front seat passengers with different restraint systems.**



**Table 8.**  
**Frequency of Abdominal Injuries Associated with the Steering Wheel for Drivers and Front Seat**  
**Passengers**

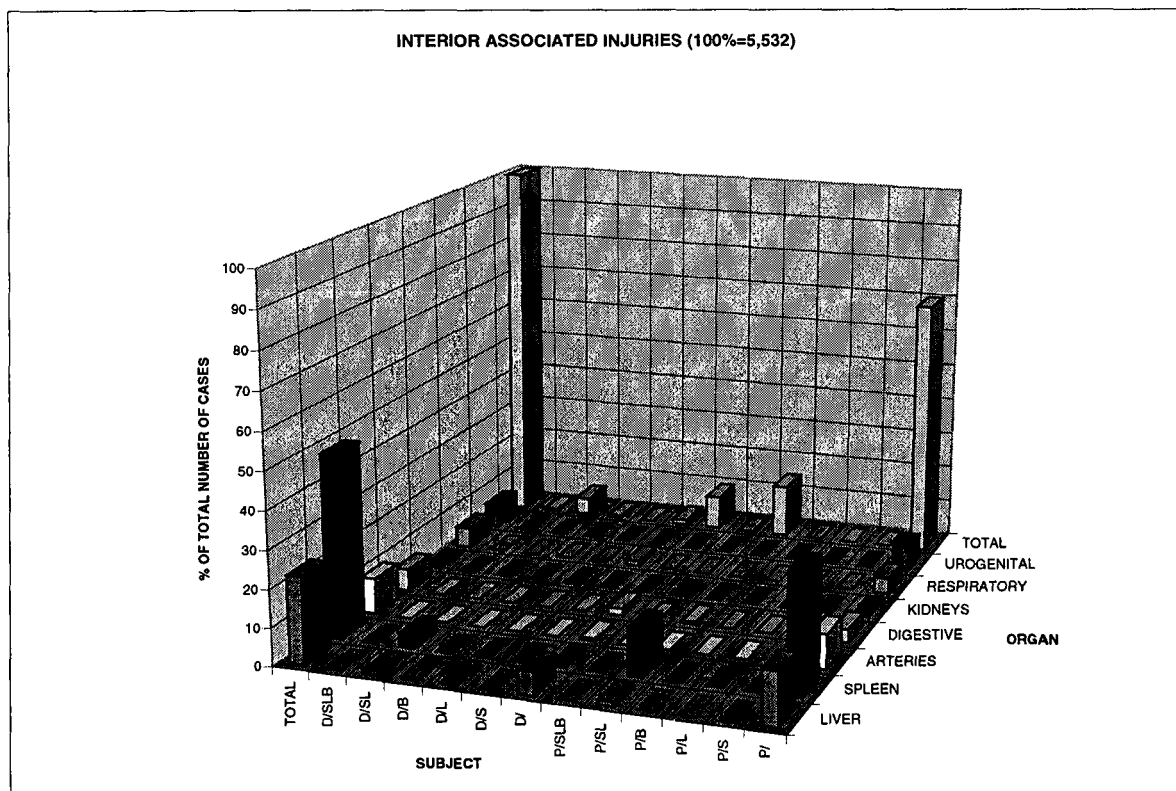
	LIVER	SPLEEN	ARTERIES	DIGESTIVE	KIDNEYS	RESPIRATORY	UROGENITAL	TOTAL
D/LSB	0.00%	0.09%	0.00%	0.00%	0.00%	0.00%	0.00%	0.09%
D/LS	0.00%	0.00%	0.02%	0.38%	0.00%	0.00%	0.00%	0.40%
D/B	0.09%	0.09%	0.00%	0.00%	0.00%	0.00%	0.00%	0.18%
D/L	0.00%	0.07%	0.00%	0.58%	0.00%	0.00%	0.00%	0.64%
D/S	11.05%	0.00%	0.00%	0.50%	0.12%	0.00%	0.00%	11.67%
D/	38.79%	19.72%	13.18%	8.26%	0.99%	3.65%	2.17%	86.75%
P/LSB	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
P/LS	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
P/B	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
P/L	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
P/S	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
P/	0.00%	0.00%	0.00%	0.00%	0.00%	0.26%	0.00%	0.26%
<b>TOTAL</b>	<b>49.93%</b>	<b>19.97%</b>	<b>13.20%</b>	<b>9.72%</b>	<b>1.11%</b>	<b>3.91%</b>	<b>2.17%</b>	<b>100.00%</b>



**Figure 5. Frequency of abdominal injuries associated with the steering wheel for drivers and front seat passengers with different restraint systems.**

**Table 9.**  
**Frequency of Abdominal Injuries Associated with the Interior for Drivers and Front Seat Passengers**  
**with Different Restraint Systems (100%=5,532)**

	LIVER	SPLEEN	ARTERIES	DIGESTIVE	KIDNEYS	RESPIRATORY	UROGENITAL	TOTAL
D/LSB	0.24%	0.24%	0.00%	0.00%	0.00%	0.00%	0.00%	0.47%
D/LS	1.06%	3.56%	0.00%	0.00%	0.00%	0.00%	0.00%	4.63%
D/B	0.56%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.56%
D/L	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
D/S	0.00%	0.00%	0.00%	0.00%	0.00%	1.27%	0.00%	1.27%
D/	6.08%	0.60%	0.57%	1.87%	0.00%	0.00%	0.00%	9.13%
P/LSB	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
P/LS	1.15%	12.40%	0.00%	0.58%	0.00%	0.00%	0.00%	14.13%
P/B	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
P/L	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
P/S	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
P/	13.88%	31.76%	9.06%	3.44%	1.00%	4.16%	6.52%	69.81%
<b>TOTAL</b>	<b>22.97%</b>	<b>48.56%</b>	<b>9.63%</b>	<b>5.89%</b>	<b>1.00%</b>	<b>5.43%</b>	<b>6.52%</b>	<b>100.00%</b>



**Figure 6. Frequency of abdominal injuries associated with the interior for drivers and front seat passengers with different restraint systems.**

## DISCUSSION

It is important to note that this study is not intended for the comparison of injury from various restraint systems. Such evaluation is problematic unless equal exposure is assumed, which is clearly not the case in this study. A clear example is the exposure of occupants restrained with lap/shoulder belt only versus with airbag only. The 1988 to 1994 NASS data used in this study were collected when less than 10% of the vehicles on the road are estimated to be equipped with airbags.

Thus, the results of this work only define the injury frequency for organs in the abdomen and the contacts associated with those injuries for the period studied. This is appropriate for the prioritization objective of this study and for injury mitigation research. Studying the association of injuries and individual occupant contacts with different restraints can serve to guide the types of measurements to be made in the crash test dummy.

The overrepresentation of abdominal injuries for higher severity corroborates the findings of previous studies (Ricci 80, Rouhana 85). This fact emphasizes the seriousness of abdominal injuries and the need for an abdominal injury detection device. Wells et al (1986) showed that belt malpositioning by occupants was common. In their study 89% of the occupants placed part of their belts above the anterior superior iliac spines (ASIS). Figure 4 highlights the need for continued effort of public education on the proper manner to wear seat belts and the need for continued research towards improved restraints.

It is well known that seat belts have an overall effectiveness of approximately 50% but the belt itself can occasionally be associated with harm to occupants (Hill, 92). Our results show that belted passengers have sustained slightly more abdominal injuries than unbelted passengers. However, these statistics do not show the fatalities and injuries to the head, neck, and chest that were prevented by these same belts. In general, the risks from the use of seat belts are overwhelmed by their ability to mitigate injury and death as has been emphasized by the literature (Backaitis 85, Rouhana 93, Evans 95).

Figure 1 also shows the higher vulnerability of the liver, spleen, and the digestive system compared to other organs in the abdomen. This is in agreement with results of a frontal impact study of the National Crash Severity Study (NCSS 1977-1988) performed by Bondy et al in 1980 (as cited in King, 1985). These results showed that the order of serious abdominal injury was liver (39%), spleen (25%), and digestive (16%). However, our study differs with Bondy's regarding kidney injury wherein he reported a frequency of 14% while we found a frequency of 4%. Since both studies agree on the three most injured organs in the abdomen, a priority for instrumentation can be determined with respect to organs injured.

Instrumentation priority from these statistics should be (in descending order): liver, spleen, and digestive system.

Our study also shows a difference with Bondy's regarding the contact points associated with abdominal injuries. Bondy reports 51% associated with the steering wheel, 48% with the interior, and 1% with the belt. Our study shows higher percentage for the steering wheel (68%) lower for the interior (14%) and much higher for the belt (17%). Those differences are most likely related to the much higher frequency of seat belt use in the period covered by our study. This might also explain the higher kidney injuries reported by Bondy. In 1977-1978, the period covered by the NCSS, belt use was around 10%. However, after the first mandatory belt use laws in 1984 belt use rose to over four times greater.

With respect to contacts associated with injury, our analysis suggests instrumentation to detect steering wheel contacts as the first priority. The second and third priorities are to the belt and interior contacts, respectively. However, given the change in restraint systems in today's vehicles, most notably the introduction of airbags, steering wheel contacts are expected to be reduced. Thus, other contacts might be higher in priority.

The direct association of the steering wheel with liver and spleen injury is expected due to the close proximity of these organs to it. Proximity may also explain the high association of the seat belt with injuries to the digestive system. Airbags were only associated with spleen injury in the abdomen. This fact highlights the vulnerability of this organ to high-pressure injuries as reported experimentally (Lau 93).

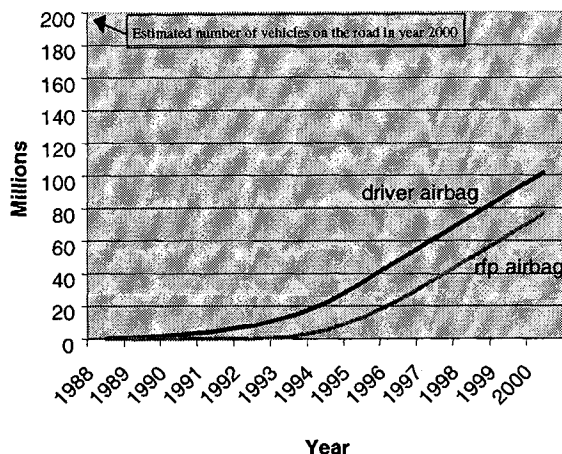
The lap/shoulder belted right front passenger shows more abdominal injuries than the right front passenger with lap belt only. The most likely reason for this is that most cars produced in the U.S. since 1972 have had lap/shoulder belts at the RFP position. Therefore, the percentage of right front passengers with lap belts only is negligible compared to those with lap/shoulder belts.

It is also interesting to compare injury frequency for the liver and spleen of drivers and passengers wearing only shoulder belts. The belted driver sustained more liver injuries compared to spleen injuries but the right front passenger saw the opposites. This can be explained by the location of the driver's shoulder belt which passes directly over the liver whereas the passenger's shoulder belt passes directly over the spleen.

The steering wheel association with the driver liver and spleen injuries can be attributed to the direct interaction of these organs with the wheel for mostly unbelted occupants. The more frequent liver injury could be due to the partial exposure of the liver outside the rib cage in contrast to the spleen, which is totally protected by the rib cage.

In contrast to steering wheel injuries, airbag and other interior objects in the vehicle are more associated with

spleen than liver injuries. These results suggest that abdominal injury patterns depend on the type of the impacted surface. The airbag and the interior can be dealt with as more load distributing surfaces compared to the steering wheel or the seat belt. These results also raise a question about the appropriateness of having the same injury criterion for localized versus distributed impacts such as seat belts versus airbags. This concept is also supported by another statistical study comparing liver and kidney injuries for belted drivers with and without airbag (Dischinger 96). The study shows 19% decrease in liver injuries and approximately 3 times increase in kidney injuries for belted drivers with an airbag. This highlights the fact that injury patterns are not stagnant. There can be a shift in injury patterns as designs or use trends change. Using data of airbag factory installation in passenger cars and trucks (from AAMA, 1996 and 1997) the estimated percentage of airbag equipped vehicles is projected to be more than half the vehicles on the road in year 2000 (Figure 8). Therefore, to comply with the objective of this study, which is to define priorities for the instrumentation of a new abdomen for the Hybrid III ATD, we need to take the increase of airbag restraints into consideration.



**Figure 7. Estimated number of airbags available for drivers and right front seat passengers on the road.**

## CONCLUSION

The results of this study will help in setting priorities for building an abdominal insert for crash test dummies. The three most frequently injured organs are in descending order: the liver (38%), the spleen (23%), and the digestive system (17%). Therefore, the abdominal insert designed should be able to assess injury to these vital organs. If the viscous criterion is used, we need to measure individual displacement and velocity of these areas. For proper identification of submarining, multiple

sensors might be required in the area over the digestive system.

The instrument most often associated with abdominal injuries was the steering wheel (68%) followed by the belt (17%) and the airbag and other interior objects (14%). One sensor over the area of the liver and one over the spleen are expected to be adequate to define injuries associated with the steering wheel. Up to three sensors over the area of the digestive system are also expected to be adequate for belt associated injuries. For more distributed loads, the type of sensor will be defined by other work as a continuation of this study.

## ACKNOWLEDGMENTS

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## THE EFFECT OF AIRBAGS ON INJURIES AND ACCIDENT COSTS

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### ABSTRACT

The global accident figures in Germany have been steadily declining for years now. This positive trend has been intensified by the extra protective effect afforded by front airbags. This additional protection of front airbags has been proven based on analyses of real accidents.

The GDV airbag database has been expanded to 335 airbag cases and currently provides information about accidents involving front and side airbags as well as "problem cases". Since the number of vehicles already equipped with side airbags is still very small in Germany, there are currently still no universally applicable findings about the behavior of side airbags.

Earlier studies carried out by the GDV clearly confirmed the protective action of the front airbag as a restraint system in addition to the three-point seat belt – primarily for the driver. The present paper focuses in particular with "airbag problems", i.e. "injuries caused by the airbag", "airbag activation while the vehicle is stopped", "airbag activation while driving" and "no airbag activation despite high accident severity". The last problem cases involved traffic fatalities. Moreover, the topic of "airbag and the cost of repair work" will also be discussed. The problem cases that are described in this paper demonstrate that the airbag itself, its components, its activation behavior, its activation threshold and the activation safety must still be optimized.

Raising the activation threshold to approx. 25-30 km/h, i.e. coordinating the activation threshold to the belted passengers, would not only reduce the danger of injury caused by the airbag itself, but would also lead to a reduction of the costs for repair work. Even today, expanses amounting to 90 million DM arise in Germany per year due to the premature activation of front airbags. When 50 % of all vehicles are equipped with airbags, this figure will rise to approximately 200 million DM. Since passenger presence detection systems only exist in very few car models, additional expenses of 70 million DM will arise per year, since in approximately 40 % of all cases involving activation of the passenger airbag, the passenger seat is not even occupied.

### INTRODUCTION

In the past few decades, the accident situation in Germany has been characterized by a steady decline in the number of traffic deaths despite a rise in traffic volume [1]. Due to improvements in automobile safety and progress in the field of accident medicine and driver education, the number of deaths among car passengers has been declining continually since 1970 (Figure 1). In 1997, there were 8,516 fatalities in Germany, two thirds of whom (5,283 persons) were car passengers.

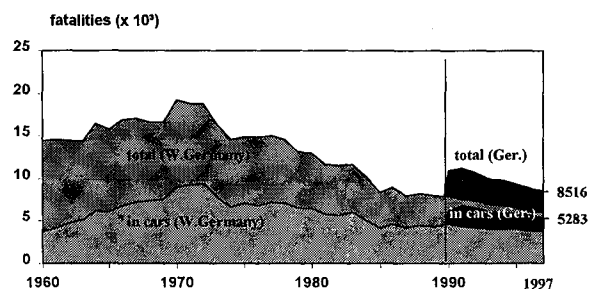


Figure 1. Number of traffic fatalities in Germany.

The reduction in the number of traffic deaths is not due to a reduction in the total number of accidents but predominantly to the avoidance of fatal injuries. The introduction of airbags will allow this positive trend to continue in the future as well – provided that the rate of seat belt use does not decline. There is hardly another safety system that has caught on as quickly as the airbag both in the consciousness of the drivers and in the design of the automobile. In the meantime, 94 % of all vehicle models destined for the German automobile market have been equipped with a driver airbag as standard equipment and as many as 75 % with a passenger airbag (with an additional 4 % added as optional equipment) [4]. The side airbag is already being installed in 11 % of all new vehicle models as standard equipment (with an additional 3 % added as optional equipment). According to estimates made by the GDV, 25 % of all automobiles registered in Germany are currently equipped with a

driver airbag, 15 % also feature a passenger airbag. The figures are rising quickly due to the fact that more than three million new vehicles are registered annually [8]. The official statistics may already be reflecting the positive impact that the airbag has had on the number of casualties in Germany (Figure 2).

Combined with the use of seat belts, the airbag has led to a new, very high level of passive safety in automobiles. A comparison of different GDV accident statistics revealed that one can assume an approx. 80 % to 90 % reduction in the risk of injury in the event of serious head-on collisions involving airbags and seat belts, compared to passengers not protected by either airbags or seat belts. Compared to the passengers secured by seat belts only, the use of an airbag and three-point belts has achieved a greater than 40 % reduction in the number of serious to fatal injuries [3].

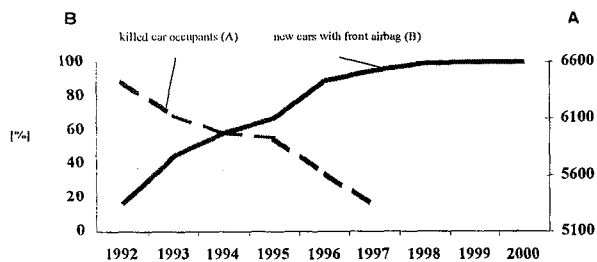


Figure 2. Killed car occupants (A) and frequency of newly registered cars equipped with front airbags (B) in Germany.

## DESCRIPTION OF THE CURRENT AIRBAG DATABASE

The accident database described in [3] (249 accidents involving vehicles equipped with front airbags) has in the meantime been expanded and supplemented by including what have been termed "problem cases" as well as accidents involving cars equipped with side airbags. A database covering a total of 335 cases involving airbags is currently available at GDV for accident research.

The present publication will focus on these "problem cases", too, and on the consequences that airbags may have on the costs of car repair and the claim expenditure on the part of car insurers. The topic of side airbags will also be discussed.

### Initial experience using side airbags

Compared to front airbags, side airbags have only been available in vehicles for a relatively short time so that the number of automobiles equipped with side

airbags in Germany is at present rather low. In spite of intensive research work and efforts devoted to this development, the accident research department at GDV currently has only very few cases involving activated side airbags.

One relevant case is described in Appendix 10. The vehicle was occupied by front-seat passengers who were secured by seat belts when the vehicle side-swiped a tree close to the right front wheel. This side-on collision triggered a total of three side airbags (the thorax side bag in the right front door, the "ITS" (inflatable tubular structure) at the front right and the thorax side bag in the right rear door). The driver, who was secured by his seat belt, remained uninjured. The front-seat passenger, also secured by a seat belt, suffered contusions and sprained his right arm.

This case involved unnecessary activation of the airbags since there was no passenger sitting at the right rear of the car and in addition even if the airbag had not been activated, it would have posed no greater risk of injury to the passenger sitting at the right front [6]. Hence, passengers involved in an accident of the type described have a relatively low risk of injury – even without the additional protection afforded by a side airbag. It cannot be stated at present to what extent this case is universally applicable since there are too few cases available that involve activated side airbags. The GDV accident research department will continue to keep a close eye on side-on collisions involving vehicles equipped with airbags and accumulate the case material, but more time is necessary.

### "Problem cases" in the airbag database

In addition to continuously expanding the database on airbag accidents, the studies conducted by GDV over the past two years have concentrated both, on the injury reducing effect of airbags and on possible "problem cases". These are understood as being the problem areas listed in Table 1, i.e. "injuries caused by the airbag",

Table 1.  
Number of "problem cases" in the GDV airbag database; cases with and without an accident

	Number
Injuries caused by the airbag	61
Airbag activation while the vehicle is stopped	7
Airbag activation while driving (without involving a collision)	7
No airbag activation despite high accident severity	5

**Table 2.**  
**Injuries caused by the airbag (cases with and without an accident)**

	Type and severity of injury	DD 0/1 No.	DD 2 No.	DD 3 No.	DD 4 No.	DD n.a. No.	SUM
Head	Facial contusion AIS 1	3	3	19	7	1	41
	Facial burns AIS 1		2	1		1	
	Hearing impairment AIS 1			1		1	
	Eye cloudiness / glaucoma AIS 1		1			1	
Cervical spine	Neck fracture AIS 6			1			1
Arm	Forearm contusion AIS 1	4	4		1	2	22
	Forearm burns AIS 1		3	3		1	
	Deep muscle injury and subluxation of thumb AIS 2		1	2			
	Chip fracture of wrist AIS 2					1	
Leg	Gash in thigh AIS 1					1	2
	Thigh contusion AIS 1		1				
	SUM	7	15	27	8	9	66

"airbag activation while the vehicle is stopped", "airbag activation while driving" (without involving a collision) and "no airbag activation despite high accident severity".

**Injuries caused by the airbag** - A total of 66 front-seat passengers were injured in the 61 cases listed in Table 1 (airbag activation with and without an accident). Depending on the degree of damage ("DD"; refer to the definition given in Appendix 1), the injuries the airbag caused to the individual parts of the body are compiled in Table 2; the AIS values [9] have been provided as well. In most cases, the injuries were minor AIS 1 injuries, although moderate injuries (AIS 2) to the arms (refer to the example in Appendix 4) and even a fatal neck fracture (AIS 6) caused by the airbag (refer to Appendix 2) were also found.

The case described in Appendix 2 is a typical "out of position" situation: the relatively small, female front-seat passenger (157 cm, 67 kg), whose seat was moved far to the front, was subjected to extremely high loads due to the activation of the full-size airbag [10]. The consequence was a massive dislocation trauma to the head and neck region with a broad dislocation between the first and second cervical vertebrae (AIS 6) due to hyperextension of the cervical spinal column. Intensive medical care kept the patient alive for almost 14 days after the accident before she ultimately succumbed to her injuries. Other fatal injuries due to the airbag in Germany, however, are not known to the GDV accident research department.

Most minor injuries (AIS 1) occurred in the head region. Approximately two thirds of all front-seat passengers suffered facial injuries when the head was contacted by the airbag. The most frequent injuries in such cases included contusions and abrasions. Two drivers reported permanent hearing impairment and one driver suffered a cataract. Four passengers sustained injuries to the face. Seven drivers suffered burns to the forearm and hand caused by the hot gases escaping from the outlet opening of the airbag at the rear of the bag.

In addition to the minor injuries and the one fatal injury described above, the airbag database also contains four moderate injuries (AIS 2) to the hand. Appendix 4 depicts a corresponding case. In an extremely minor rear-end collision, the front-seat passenger, who was secured by a seat belt, propped himself up against the instrument panel in a reflex action. He suffered deep lacerations on both hands between the thumb and index finger including injury to the muscles and a subluxation of the saddle joint of the thumb caused by the airbag cover. These injuries were evaluated as being AIS 2.

As long as the airbag has provided protection and spared the passengers serious injury in the event of a severe collision, then such accompanying injuries can still be tolerated, provided they are in the range of AIS 1 or AIS 2 injuries. However, if these injuries are caused by the airbag activation at low speeds corresponding to a deformation pattern of EES  $\leq 30$  km/h, then the injured person will consider such injuries as inadequate. In this speed range, the safety belt reliably protects the



**Table 3.**  
**Airbag activation while the vehicle is stopped**

Vehicle	Model	Circumstances	Cause	Injuries
No. 1	1995	driver airbag activated when starting engine	unknown	minor complaints of cervical spine
No. 2	1994	driver airbag activated when driver was getting out of car and had removed ignition key	unknown	contusions of arm, thorax
No. 3	1994	driver airbag activated when driver was getting out of car and had removed ignition key	unknown	bitten tongue
No. 4	1985	driver airbag activated when driving in reverse gear	unknown	contusions
No. 5	--	driver airbag activated when engine was jump-started	severed cable under the ignition lock owing to attempted theft	no injuries
No. 6	--	driver airbag activated when driver was getting out of car	unknown	no injuries
No. 7	1994	driver airbag activated when driver was getting out of car and had removed ignition key	unknown	wrist contusion

passenger from serious injury and it is therefore unnecessary to actuate the airbag, thus causing contusions, abrasion or even burns and lacerations which would not have occurred if the airbag had not been activated.

**Airbag activation while the vehicle is stopped** - Among the "problem cases", there are seven cases in which the driver airbag activated while the vehicle was not moving (without any external application of force due to an accident). Table 3 contains both the circumstances as well as the known causes of airbag activation including the injuries sustained by the drivers.

These incidents did not cause any major injuries to the drivers; injuries exceeding AIS 1 did not occur. Contusions on the arm and wrist were both documented because the airbag hit the upper extremities as the driver was getting out of the car. There were also thoracic contusions and a bitten tongue. One driver suffered minor cervical whiplash complaints because the driver airbag inflated while the driver was starting the engine.

In four of the seven cases, the airbag inflated while the drivers were getting out of the car. In many cases, the ignition key had already been removed from the ignition lock by this time (refer to the case described in Appendix 7).

The reasons for activation of the driver airbag were able to be reliably explained in one case only: cables that had been severed during an attempted theft caused a short circuit which led to the activation of the driver

airbag. In all other cases, the reasons remained a matter of speculation.

**Airbag activation while driving** - As already illustrated in Table 1, the GDV airbag database contains seven cases in which the airbag was activated while the vehicle was moving (without any involvement in an accident). The exact circumstances, the reasons that have become known and the injuries that the passengers suffered can be seen in Table 4. As in the case of airbag activation while the vehicle was not moving, the passengers in the cases mentioned here went uninjured or sustained only minor injuries (AIS 1). The injuries were limited to abrasions, contusions and burns on the arms as well as facial abrasions.

Impact to the floor pan of the vehicle was the principal cause of airbag activation while the vehicle was moving in a total of four cases. This impact to the floor pan originated from driving over a traffic island, from making contact with the exit ramp of a multi-story parking garage (refer to Appendix 3) and from making contact with a tipped-over barrier post (refer to Appendix 8). The damage done to the underside of the vehicle infer that the force as well as the associated deceleration was either transmitted to the frame directly (tow-hook) or were transferred via the sump pan and gearbox transmission to the longitudinal beam, thus causing the airbag to actuate. Even in the one case involving activation of the side airbag on the driver side while overtaking another vehicle, the technical

Table 4.  
Airbag activation while driving (without involving a collision)

Vehicle	Model	Circumstances	Cause	Injuries
No. 1	1997	(driver) side airbag activated while passing another car	contact with the underside of vehicle	minor injuries to arm
No. 2	1996	driver and passenger airbags are activated when car drives over a traffic island	strong impact on left front wheel, chassis and transmission	burns and abrasions on forearm and hands
No. 3	1995	driver and passenger airbags are activated when car runs over tipped-over barrier post	contact with the underside of vehicle	unknown
No. 4	1995	driver and passenger airbags are activated when car runs over exit ramp in parking garage	contact with the underside of vehicle	both driver and passenger have abrasions
No. 5	1995	driver airbag is activated at 25 km/h	impact from beneath due to bump in road	abrasions to the face
No. 6	1994	driver airbag is activated when car starts to move	moisture in the control mechanism	none
No. 7	1986	driver airbag is activated when parking the car (without collision)	short circuit between sliding contacts due to two loosened screws	contusions on arms

inspection of the vehicle by the automobile manufacturer revealed signs of impact on the floor pan of the vehicle.

In another case, moisture in the control mechanism was the cause of airbag activation while driving. The driver airbag was activated while the vehicle was moving without a collision or any other type of external force being applied. According to the car manufacturer, moisture was found in the control mechanism, although it was still intact. This moisture caused an interference voltage which ultimately could have caused the airbag to actuate. The car manufacturer had not been able to determine any other causes.

Finally, the GDV accident research department became aware of a case involving a technical defect in the form of a short circuit between the sliding contacts. The driver airbag activated while the car was being parked in a parking space (with no collision involvement). It was found during the subsequent repair work that two screws of an anchor plate had loosened, thus causing a short circuit between the contacts.

**No airbag activation despite high accident severity** - Collisions with a relatively high accident severity ( $DD \geq 3$ ; refer to the definition in Appendix 1) involving a vehicle equipped with airbags which fails to inflate are comparatively rare, although a total of five cases were found in the GDV airbag database in which at least one airbag failed to activate.

Table 5 contains these five cases. The injuries to the front-seat passengers were very serious in several cases and even fatal in one case. Both the severity of injuries and the degree of damage make it clear that in these cases the airbag could have actually provided the greatest

protection [3].

Case B is illustrated in Figure 3. Looking at such an accident, it becomes clear that the driver airbag should have activated under all circumstances. The reason the airbag failed to activate was due to a connector that had been forced open so that the airbag could not have activated. A similar case involving an improperly closed connector where there was no connection to the driver airbag module (see Appendix 9) has already been published in the German automobile press [11]. The driver was killed in this case as well.

In case D contained in Table 5 (refer to Appendix 6), the front-seat passenger was seriously injured because the passenger airbag failed to activate. That the activation threshold had been reached in this case is confirmed by the fact that the driver airbag did in fact activate. The reasons submitted by the car manufacturer was that it was not possible to activate the passenger airbag, since the cables of the passenger airbag circuit had been severed as a result of the accident. The same automobile manufacturer is known to be involved in another case with a similar accident severity in which the reason for the non-activation of the passenger airbag was stated as being "inadequate energy input into the passenger airbag circuit".

It is not always vehicle defects, however, that cause the airbag to fail to activate. GDV knows one case (case E in Table 5) in which the steering wheel had been interchanged improperly. This thus caused damage to the spiral spring which in turn was the reason the airbag failed to activate.

In summary it has to be pointed out that failure cases are extremely rare, but these cases occur.

**Table 5.**  
**No airbag activation despite high accident severity**

Vehicle	Model	Circumstances	Cause	Injuries	DD
A	1992	collision with guard rail, no airbag activation	unknown	slight injury of the cervical spine, pulled muscles in forearms	3
B	1995	head-on collision with a tree; driver airbag activated, passenger airbag did not	connector to the driver airbag had been forced open	driver killed (sole passenger))	4
C	1993	head-on collision with a tree; driver airbag activated, passenger airbag did not	probably inadequate energy input into the passenger airbag circuit	driver (sole passenger) sternal fracture, scratches on the arms, contusions of the legs	3-4
D	1997	head-on collision with a tree; driver airbag activated, passenger airbag did not	the cables of the passenger airbag circuit had been severed as a result of the accident	driver slightly injured, front-seat passenger suffered serious brain concussion, lacerations and contusions to the face and body	4
E	---	passenger airbag activated, driver airbag did not	damage to the spiral spring due to improper exchange of the steering wheel	unknown	3



Opel Astra:

Collision with a tree

Injuries to the belted driver: Critical craniocerebral trauma  
Critical thoracic and abdominal injuries

**AIS 6**  
**AIS 6**

**Figure 3.** Severe frontal collision with fatal injuries to the belted driver (sole passenger); passenger airbag activated, driver airbag not activated.

## AIRBAG AND REPAIR COSTS

### Unnecessary activation of the passenger airbag

It was found in [3] that (in real accidents) the current non-intelligent generation of airbags was activated entirely unnecessarily on the passenger side in 42 % of all cases. In 34 accidents out of a total of 82 in which the passenger airbag was activated, there were not even a passenger sitting in the car. It is therefore indispensable that all vehicles equipped with a passenger airbag be provided with a passenger presence detection system as well.

A computer-assisted assessment of damage calculations of two comparable types of vehicle with and without a passenger presence detection produced the following situation with respect to the activation frequency of the airbag and the costs of repair: as vehicle "1" was not equipped with a passenger presence detection, all passenger airbags were activated together with the driver airbag. In vehicle "2", the passenger presence detection prevented the passenger airbag from activating when the passenger seat was vacant in 96 % of all cases in which the driver airbag was activated (Figure 4). This shows that a higher firing level and a passenger presence detection would essentially contribute to less unnecessary deployment of airbags on the passenger side, without reducing the protection effect. If passenger presence detections had been provided in all vehicles equipped with an airbag, annual repair costs amounting to approx. 70 million DM could have been avoided in Germany.

### Low activation threshold

The analysis of real accidents [3] shows that approximately 50 % of the airbags are activated in the EES range of 15 km/h. This experience from real accidents has been verified in low speed crash tests as well. At the Allianz Center for Technology, standardized low speed crashes were conducted at 15 km/h and with 40 % offset against a rigid barrier to determine the repair costs for head-on, side-on and rear-end collisions. During these tests, the airbags were activated in a number of vehicles even at these low collision speeds. In these cases, in addition to the extent of damage to the car body, the repair costs tend to be driven up by an additional 8-31 % if only the driver airbag needs to be replaced and by 47-56 % for vehicles equipped with two airbags (Figure 5).

In real traffic accidents that occurred at a low collision speed, the costs of repairs for the airbag-induced damage was twice to three times as high as the actual repairs caused by the accident itself (see Figure 5). In the first of the cases depicted here, the impact of the front tires against the curb was enough to trigger the driver airbag. The result drove the costs of repairs up by 240 % due to the fact that the airbag had been activated (replacement of an aluminium rim and two tires = 1,153 DM in addition to the driver airbag = 2,763 DM). In a second case, the fender had to be replaced after a very minor frontal collision. The seat belts had to be replaced since the seat belt pretensioner had been actuated, something that can be readily accepted. In addition to this, however, the activation of the driver and passenger

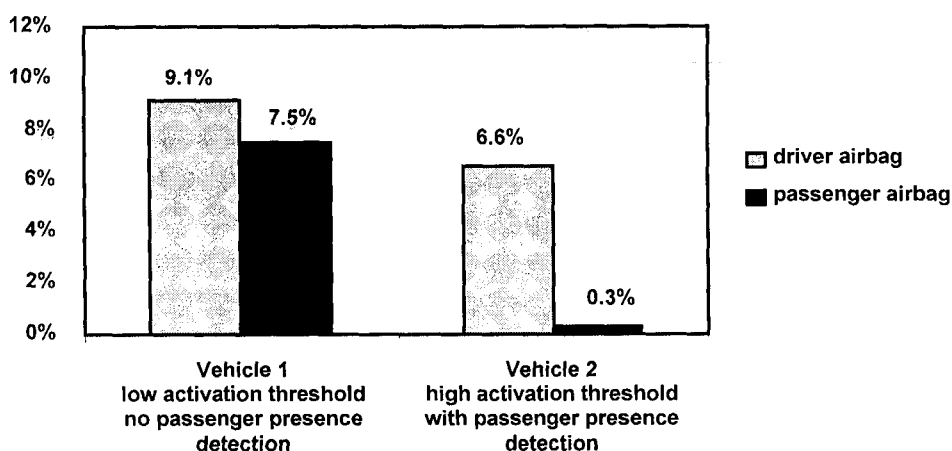


Figure 4. Frequency of driver and passenger airbag activation in two comparable vehicles with and without passenger presence detection.

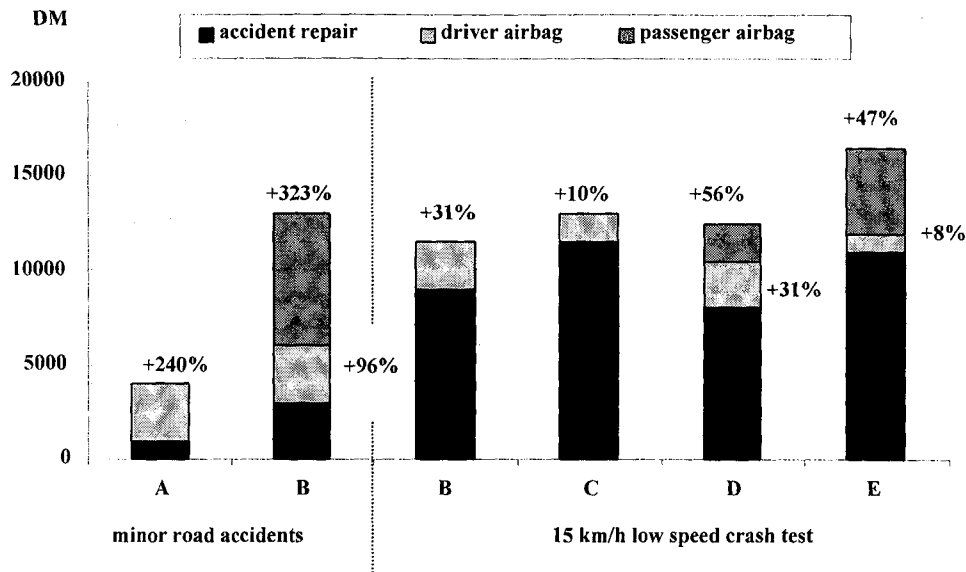


Figure 5. Increase in repair costs caused by driver and passenger airbag activation.

airbags had not only demolished the dashboard and the windscreen, the sunroof had also been damaged due to the pressure wave. In addition to the repair work of the car body (3,000 DM) the total costs rose to 10,000 DM owing to the damage caused by the airbags.

A conservative estimate (assuming that 25 % of all vehicles are equipped with a driver airbag and 15 % with a passenger airbag) indicates that even today the costs of repairs has increased approximately 90 million DM per year owing to the unnecessary early activation of airbags. As more and more automobiles are equipped with airbags, it is quite possible that a figure amounting to about 200 million DM will be reached quickly within the next few years.

In addition to an activation threshold which is often much too low, airbag activation – especially on the passenger side – not infrequently causes needless damage to the passenger compartment so that the windscreen and the entire length of the dashboard, for example, must be replaced. A comparison of the costs of repair work with and without airbag activation for one and the same type of vehicle showed [5, 7] that the vehicle was a write-off in 36 % of all accidents. Hence, the additional costs were irrelevant. In approximately one fourth of all cases, however, the damage caused by the needless activation of the airbag during the accident and the resultant higher costs of repair reached or exceeded the amount of a total write-off.

Engineers are faced with the real challenge of avoiding such unnecessary and costly damage by intelligent solutions to accident repair work.

#### Added costs due to the airbag

In yet another cost analysis, an attempt was made to estimate the proportion of additional airbag repair costs in full comprehensive vehicle insurance for the entire German insurance market.

The study was based on a random sample taken from a total of six design series being on the German market for less than two years. All vehicles in these design series were equipped with airbags as standard equipment from the very beginning of production.

The average additional costs per airbag repair (costs of labor and spare parts) were calculated for these vehicles. The added cost expenditure which car insurers had to pay in settlement for airbag repairs within the framework of full comprehensive vehicle insurance was calculated on the basis of the number of airbag modules exchanged in the respective design series.

Based on the total amount of costs paid in settlement and the number of insured vehicles in the respective design series, the costs of repairs for airbag damage amounted to approximately 2.5 % for the chosen random sample. If this value is extrapolated for the total market, the result is a sum amounting to approximately 200 million DM per year. Against the background of an increase in the number of vehicles being equipped with airbags and with more side airbags now being installed in cars in addition to the front airbags, an increase in the costs of airbag-induced repair work must be expected in the future.

## SUMMARY AND CRITICAL DISCUSSION OF KEY POINTS

The number of deaths due to traffic accidents has continued to decline in the past few decades in Germany. The most recent official statistics concerning road fatalities may well show this positive initial impact of the added protection the airbag offers to car passengers.

The GDV airbag database has been expanded continuously and now provides accident research with 335 cases involving airbags (accidents involving front and side airbags as well as "problem cases"). Unfortunately, the number of vehicles equipped with side airbags is still so low in Germany that no statistically reliable data, but only case reports, can be presented. The case material, however, will be continuously supplemented in the future.

The study confirmed former results on the injury reducing effect of airbags, but showed some "problem cases", especially "injuries caused by the airbag", "airbag activation while the vehicle is stopped", "airbag activation while driving" (without involving a collision) and "no airbag activation despite high accident severity". These problem cases as reported have to be excluded in the future as far as possible.

"Injuries caused by the airbag" are normally limited to AIS 1 injuries, although moderate injuries (AIS 2) and one fatal injury (AIS 6) have also been registered. If the airbag fulfills its protective function in the event of a serious collision and has protected the passengers from severe injury, then AIS 1 or AIS 2 have to be tolerated. However, if the activation of the airbag causes these injuries, in particular at low speeds up to an EES of 30 km/h, then those injuries are totally unnecessary. Seat belts still reliably protect passengers from serious injury at this speed range. It is therefore unnecessary to activate the airbag in this situation, thus giving rise to contusions, abrasion or even burns and lacerations which would not have occurred had the airbag not been activated.

Airbag-induced injuries could be avoided not only by raising the activation threshold of the airbags, but also by using "smart" systems capable of detecting the seating position of the passenger including his/her height and weight.

But even minor injuries (AIS 1) should not be endured uncritically. The incidence and severity of burns (refer to Appendix 5), for instance, could be diminished by modifying the airbag fabric, the outlet openings and airbag cover and by optimizing the hybrid gas generators. Additional innovative solutions need to be found in this respect.

The seven cases of "airbag activation while the vehicle is stopped" prove that activation of the airbag is

possible even without the effect of external forces and even after the ignition key has been removed from the ignition lock. In the cases so far known, the passengers suffered only minor injuries or none at all, but there is a risk which should not be underestimated. The fact that the airbag is capable of causing fatal injuries when a person is seated very close to the airbag is proved by the case described in Appendix 2. Hence, cases of airbag activation while the vehicle is stopped must be precluded using all technical means available.

The GDV airbag database currently contains seven cases in which the airbag was activated while the vehicle was moving. The severity of the injuries sustained by the passengers was at most AIS 1 – similar to airbag activation while the vehicle is stopped. In four of the seven cases, impact to the floor pan of the vehicle was the cause of the activation. The problem is that the airbag electronics system apparently interpreted the impact as if an accident had in fact occurred. New intelligent ("smart") systems featuring improved interpretation of acceleration signals should therefore be developed.

A misinterpretation of the acceleration signals was evidently not involved in any of the five cases in which the airbag failed to activate in spite of high accident severity. On the contrary, these cases involved defects in the airbag circuit (poor connectors, severed cables, damaged spiral springs, etc.). Since the consequences of the accidents were in some cases very severe or even fatal injuries, the entire airbag system including all relevant components should be installed in the vehicle with the utmost care.

Today, the passenger airbag is activated in many cases (42 % in the GDV accident database), although the passenger seat is vacant. Extrapolations for Germany have revealed that this causes added expenditure of approximately 70 million DM in repair costs per year. As more and more vehicles are equipped with airbags, this expenditure will continue to rise unless passenger presence detection systems are provided in all cars.

The activation threshold of current airbags is much too low. Even at low speeds (EES about 15 km/h) there was airbag activation in 50 % of the cases. The results from low speed crash tests have verified this fact.

Besides unnecessary risk of injury, which is not always low, added repair costs are to be expected with about 200 million DM by the year 2000, when more than 50 % of all vehicles will be equipped with airbags. The activation threshold of future airbag systems should therefore correspond to a wall impact speed of approx. 25 km/h to 30 km/h and the activation characteristics should be geared to passengers wearing seat belts. Marketing considerations should in no way prevent or even impede the optimum design and construction of

protection systems.

Earlier studies [3, 7] clearly confirmed the protective effect of the front airbag as an additional safety system which supplements the three-point seat belt: The maximum injury severity MAIS to belted drivers in frontal impacts with and without airbag deployment as a function of the degree of damage (DD) is shown in Appendix 11. In a comparison with the accident material of the Vehicle Safety 90 [2] it becomes clear that with the same car damage the drivers are far more rarely severely injured or killed when the airbag deploys. This becomes especially clear in the 3 to 4 range of degrees of damage, i.e. a relatively high accident severity. In the airbag material, only in the case of high car deformation (DD 4) did serious MAIS 3-4 injuries occur, and there were no fatal injuries at all with this accident severity. Only in so-called disaster cases with extreme intrusion into the passenger cell (DD 5) was a fatally injured driver observed in the airbag material.

The airbag therefore was - and still is - a major step towards greater safety. It is thus all the more important to take the few problem cases seriously and eliminate risks which could discredit the airbag from the outset.

#### ACKNOWLEDGEMENTS

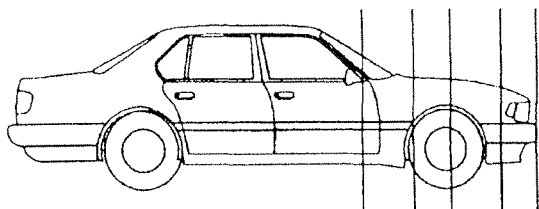
The authors gratefully acknowledge Wilfried Klanner and Hubert Paulus (ADAC) for their considerable support in collecting the airbag cases; Harthmut Wolff (Allianz Center for Technology) for his work concerning the repair crash tests; Jürgen Redlich (GDV, Department of Car Insurance) for his estimate of airbag repair costs in full comprehensive vehicle insurance and Tobias Bente (GDV, Institute for Vehicle Safety) for the evaluation of the airbag material and for producing the figures and tables of this paper.

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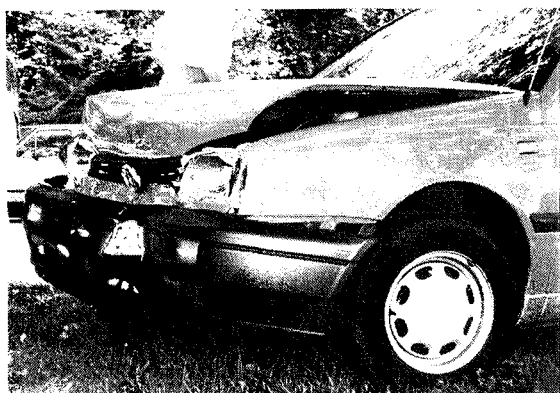
## Appendix 1

### Examples of Degree of Damage Classification



5 4 3 2 1

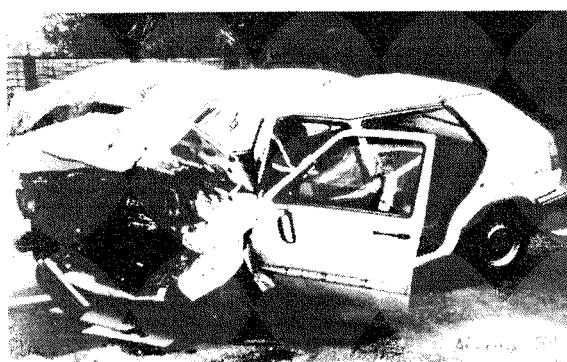
Degree of damage 1 = light  
(corresponds to minor scratches, dents, etc.)



Degree of damage 2 = moderate



Degree of damage 3 = severe



Degree of damage 4 = extreme



Degree of damage 5 = total



## Appendix 2

### „Airbag Material“ Case No.: 273

**Airbag vehicle:** Mercedes E 220 (124); Taxi  
driver and passenger airbags activated

EES = 30 km/h



#### Injuries to the not belted driver:

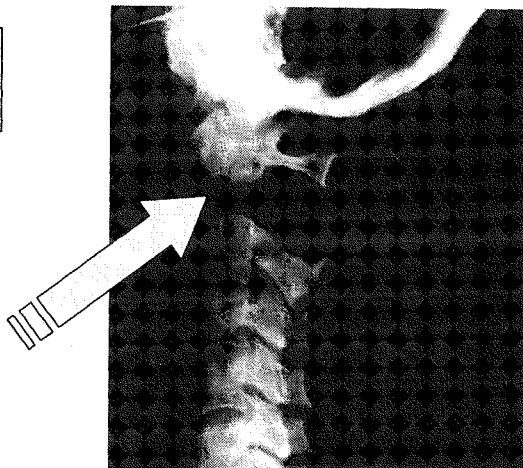
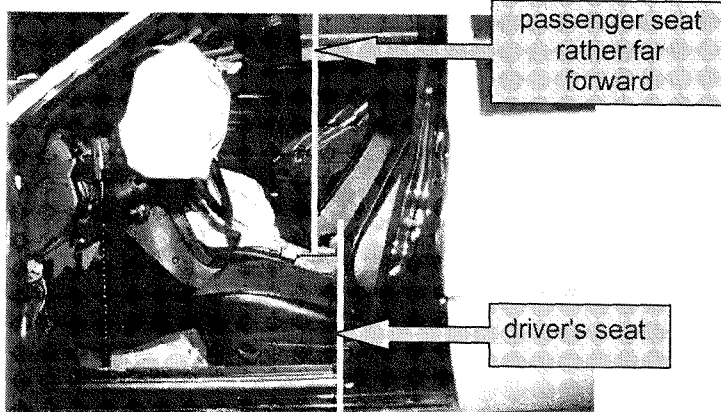
- contusion to the left knee

AIS 1

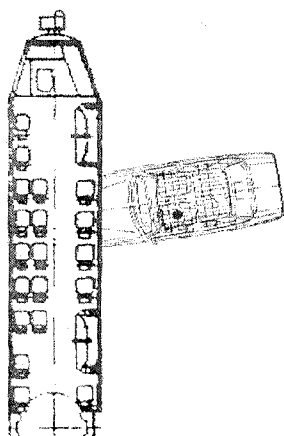
#### Injuries to the female, belted passenger:

- hyperextension trauma with fracture of the cervical spine between the 1<sup>st</sup> and 2<sup>nd</sup> cervical vertebrae

AIS 6



**Accident opponent:** streetcar



## Appendix 3

### „Airbag Material“ Case No.: 14

**Airbag vehicle:** Mazda 323  
driver and passenger airbags activated



**injuries to the belted driver:**

- facial contusions AIS 1

**injuries to the female, belted passenger:**

- facial contusions AIS 1

**Accident opponent:** exit ramp of a parking garage



## Appendix 4

### „Airbag Material“ Case No.: 15

**Airbag vehicle:** Vw Golf III  
driver and passenger airbags activated

EES = 10 km/h



#### **Injuries to the female, belted driver:**

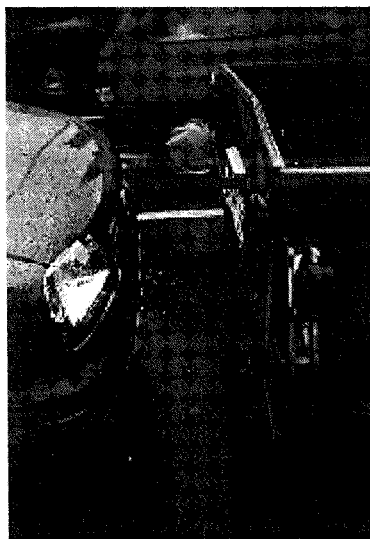
- no injuries

#### **Injuries to the belted passenger:**

Deep lacerations between the thumb and index finger of both hands with injury to the muscle tissue and subluxation of the saddle joint of the thumb

**AIS 2**

**Accident opponent:** frontal collision with a trailer



## Appendix 5

### „Airbag Material“ Case No.: 21

**Airbag vehicle:** MB 200 E  
driver and passenger airbags activated



the damaged site in the driver airbag



#### **Injuries to the female, belted driver:**

- 2<sup>nd</sup> degree chemical burns to the face
- contusions on the thorax
- contusions on the left arm

**AIS 1**

**AIS 1**

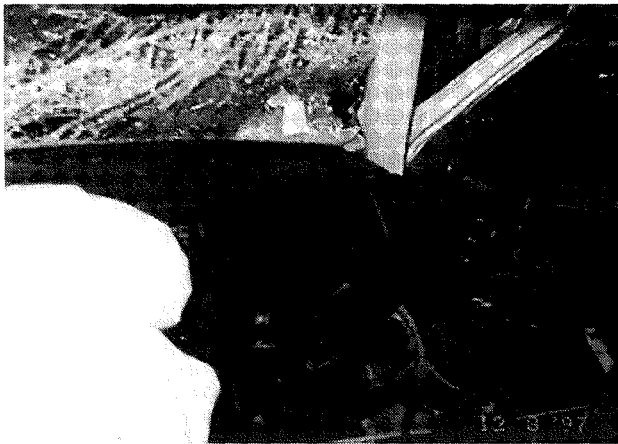
**AIS 1**

**Accident opponent:** collision with a post

Appendix 6

**„Airbag Material“  
Case No.: 8**

**Airbag vehicle:** VW Golf  
driver airbag activated, passenger airbag not activated



**Injuries to the female, belted driver:**

minor injuries  
(without further details)

**AIS 1**

**Injuries to the belted passenger:**

- facial lacerations
- cerebral concussion

**AIS 1**

**AIS 2**

**Accident opponent:** collision with a tree

## Appendix 7

### „Airbag Material“ Case No.: 6

**Airbag vehicle:** AUDI 80  
driver airbag activated, no passenger airbag installed



#### injuries to the driver:

- contusions on the right arm
- contusions on the right thorax

**AIS 1**

**AIS 1**

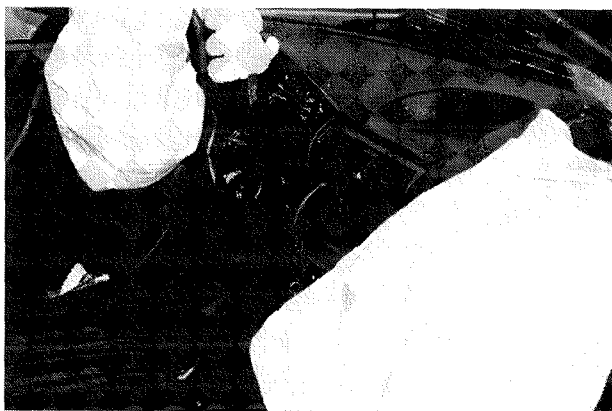
**Accident opponent:** no collision

The driver airbag activated when the driver was getting out of the car  
(ignition key had already been removed from the lock)

## Appendix 8

### „Airbag Material“ Case No.: 13

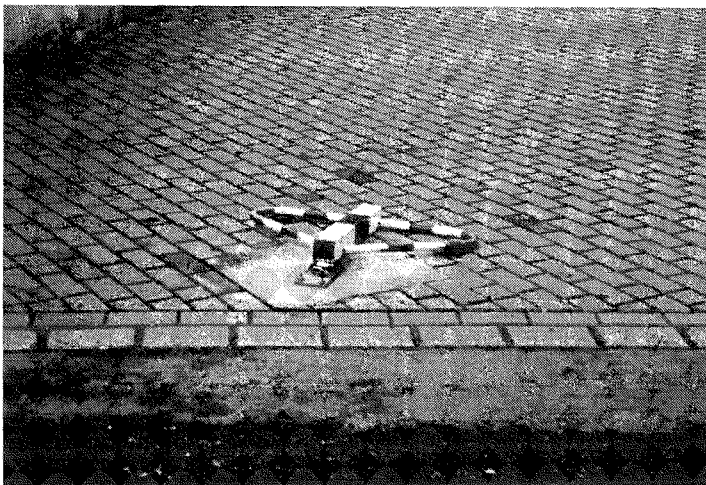
**Airbag vehicle:** Opel Astra  
driver and passenger airbags activated



**Injuries to the passengers:**

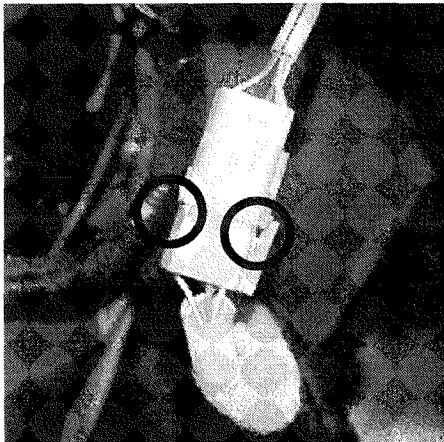
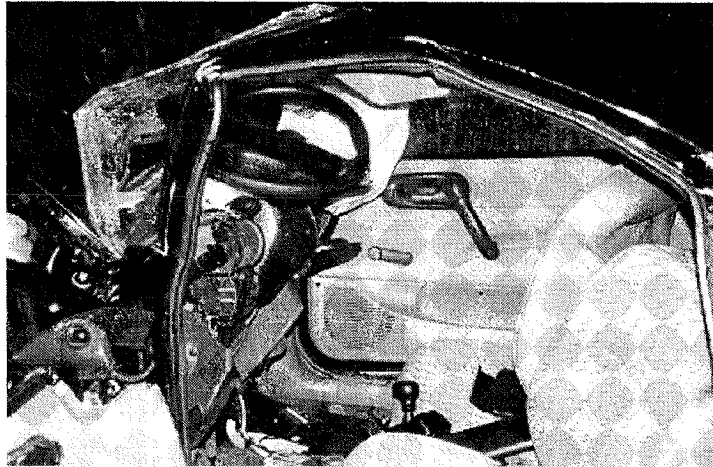
No injuries

**Accident opponent:** floor contact with a barrier post



**„Airbag Material“  
No Case No.**

**Airbag vehicle:** Opel Corsa  
passenger airbag activated, driver airbag not activated



**Injuries to the female, not belted driver:**

- fatal injuries (not further specified)

**Injuries to the female, not belted passenger:**

- serious injuries (not further specified)

**Injuries to the not belted back-seat passenger:**

- serious injuries (not further specified)

**Accident opponent:** Renault Megane

Source: „ams“ Nov. 1997 [11]



**„Airbag Material“  
Case No.: 41**

**Airbag vehicle:** BMW 540i  
ITS and thorax airbags activated



**Injuries to the belted driver:**

No injuries

**Injuries to the female, belted passenger**

- contusions on the right arm
- AIS 1**



**Accident opponent:** collision with a tree

**Airbag Material - Distribution of the Driver's MAIS  
as a Function of the Degree of Damage**

Driver Airbag Deployed, Frontal Impact, Driver Belted								
Degree of Damage	MAIS							Total
	0	1	2	3	4	5	6	
DD 1 - light								
DD 2 - moderate	35%	53%	12%					100% = 34
DD 3 - severe	13%	67%	20%					100% = 64
DD 4 - extreme	8%	24%	44%	12%	12%			100% = 25
DD 5 - total			50%				50%	100% = 2

**VS 90 - Distribution of the Driver's MAIS  
as a Function of the Degree of Damage [2]**

VS 90 Frontal Impact, Driver Belted								
Degree of Damage	MAIS							Total
	0	1	2	3	4	5	6	
DD 1 - light	52%	47%	1%					100% = 394
DD 2 - moderate	34%	63%	3%	0.2%				100% = 2,178
DD 3 - severe	12%	68%	16%	3%	0.7%	0.1%	0.3%	100% = 1,402
DD 4 - extreme	1%	28%	33%	20%	9%	3%	6%	100% = 391
DD 5 - total		4%	13%	9%	20%	7%	47%	100% = 54

# Technical Session 2

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## Intelligent Transportation Systems (ITS) Collision Avoidance Systems

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Chairperson: Y. Ian Noy, Transport Canada, Canada

The International Harmonized Research Activities (IHRA) Status Report of the Intelligent Transportation Systems (ITS) Working Group was presented at the onset of this Session during the 16<sup>th</sup> ESV Conference. This Report begins Technical Session 2.

## INTERNATIONAL HARMONIZED RESEARCH ACTIVITIES (IHRA) STATUS REPORT OF THE INTELLIGENT TRANSPORTATION SYSTEMS (ITS) WORKING GROUP

Y. Ian Noy  
Transport Canada  
Canada

### PURPOSE OF IHRA-ITS WG

The goal of the research coordinated by the IHRA-ITS WG is to develop procedures (including methods and criteria) for the evaluation of safety of in-vehicle information, control and communication systems with respect to human performance and behaviour. These procedures are intended to address cross-cutting issues rather than to focus on specific applications.

### BACKGROUND

#### IHRA

The International Harmonized Research Activities is an inter-governmental initiative which aims to facilitate greater harmony of vehicle safety policies through multi-national collaboration in research. IHRA is organized under the auspices of Enhanced Safety of Vehicles<sup>†</sup> (ESV) representing the U.S., UK, Canada, the Netherlands, Germany, Australia, Sweden, Japan, France, Italy, Hungary, and Poland. In addition, the European Commission (EC) and the European Enhanced (Safety) Vehicle Committee (EEVC) are represented. The Working Group on ITS is one of five working groups addressing high-priority research needs.

The impetus behind this WG reflects the need for governments to understand and minimize the potentially adverse impacts of ITS technologies and to incorporate safety assurance into system development. Within the domain of ITS, traditional approaches to government intervention are limited by the lack of timely field data needed to support interventions, and the lack of a priori

knowledge of system functionality needed to develop performance criteria.

Harmonized research in ITS is of special importance for three reasons, 1) it represents a significant opportunity to influence active safety<sup>‡</sup> through effective collision avoidance intervention, 2) it addresses a global need to more clearly define the role of government with respect to ITS safety, 3) driver-ITS interaction is an area essentially unregulated at the present time; consequently, there is a greater likelihood of achieving harmonized safety policies than might otherwise be the case.

#### Safety Risks of ITS

The advent of ITS is revolutionizing motor vehicle transportation. Not only is the nature of driving changing radically, but it will likely be in a continuing state of flux, at least in the foreseeable future, as technologies continue to evolve. It is extremely important to ensure that new systems and technologies are guided by human factors principles and data so that they do not lead to driver behaviours and responses which are not intended by systems designers. In aviation, for example, increased pilot assistance and automation has unwittingly reduced situational awareness and produced out-of-the-loop performance problems (i.e., increased errors and response latency). There are both micro-level (the direct effects on individual drivers) and macro-level (the effects on the overall traffic system) considerations<sup>††</sup>. The risks associated with increased automation (e.g., behavioural adaptation, mixing intelligent and conventional vehicles, loss of skill, negative transfer, and driver reliance on fallible technologies) are not well understood and cannot be reliably predicted at present.

It is essential to recognize that intelligent technology per se is neither inherently beneficial or detrimental to safety. The impact of technological change on safety will depend on its implementation and, in particular, on the extent to which the system supports drivers' needs and is

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<sup>†</sup> Enhanced Safety of Vehicles is an international forum for the exchange of scientific and technological advances in vehicle safety. Until recently, the principal activity of ESV was the biannual conference which brings together motor vehicle research administrators from government and industry to explore measures to reduce the risks and consequences of motor vehicle collisions. The conference continues to be a major, though no longer the only, activity of ESV. IHRA is an initiative which has recently evolved out of the ESV conferences.

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<sup>‡</sup> Active safety (also known as primary safety or collision avoidance) refers to countermeasures which are designed to prevent collisions from occurring.

<sup>††</sup> See Noy, Y.I., 1997, Human Factors in Modern Traffic Systems. Ergonomics 40(10), Taylor & Francis.

compatible with human capabilities and limitations. The primary human factors issues concern central human processes such as situational awareness and cognition. Secondary issues concern peripheral processes (e.g., legibility) that are affected by the physical design of the human-machine interface.

The WG on ITS was established to help governments to better understand the safety benefits and risks associated with on-board ITS and to recommend a generic framework for evaluating the safety of driver-ITS interactions.

## SCOPE

The WG is a forum for multi-national research with the aim to develop safety evaluation procedures that can form the basis of harmonized national policies on ITS<sup>1</sup>. It is recognized that industry's role is to develop products that are effective, safe and acceptable to the public. Government's role is to ensure that products comply with appropriate safety criteria. The development of such criteria is the *raison d'être* of this WG. It should be noted that while there are numerous groups developing ITS standards and operational requirements, no other body is developing procedures for evaluating the safety of on-board ITS devices.

Certain intelligent technologies are being developed with the express purpose of assisting drivers to avoid collisions (e.g., so-called collision avoidance systems include forward obstacle collision warning system, lane departure warning systems and fatigue warning systems); whereas other systems are being developed to enhance driver convenience (e.g., navigation, adaptive cruise control). Since both types of systems can affect safety, the framework is intended to apply to all on-board information, control and communication systems, whether they be collision avoidance systems or driver convenience features.

The WG is concerned with summative evaluations; that is, final test and evaluation of systems prior to their introduction into the market. It is recognized that during

their development, systems undergo design iterations that involve the collection and analysis of relevant human performance and other data. These formative evaluations are conducted at various stages of system development to check system performance against corporate objectives and specifications. They are primarily within the control and serve the interests of industry and, as such, are beyond the scope of this WG. While formative evaluations are important and can contribute to overall system safety, safety assurance relies on evaluations of systems that are ready for implementation in the real world.

The procedures considered by this WG for the safety evaluation of ITS apply to all on-board systems that involve driver interaction (either directly or indirectly) and take into consideration the influence of human factors ranging from behavioural adaptation to driver reactions to possible system failures. It is intended that the evaluation of a system (whether it is an individual component or an integrated multi-function interface<sup>2</sup>) be performed in the vehicle(s) for which such a system is designed.

## SAFETY ASSURANCE MODEL

This WG is not concerned with all aspects of ITS safety and is not the only body concerned with ITS safety. In order to illustrate the role of the IHRA-ITS WG in relation to that of other groups, a simplified model of ITS safety assurance is presented in Figure 1. The model posits that safety is optimized by (1) adherence to accepted safety principles, (2) conformity with existing human-machine interface (HMI) standards, (3) conformity with minimum criteria for collision avoidance systems (CAS), if applicable, and (4) implementation of a safety assessment program. These are shown in the model as four separate blocks and are briefly described in the sections which follow in order to elaborate the model. While all of these elements are important for safety, the work of the IHRA-ITS WG is focused on developing a framework for final test and evaluation of system safety. This element is indicated in the figure by the shaded block. Other organizations are involved with other blocks of the model, as described in the sections below.

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<sup>1</sup> Policies can take the form of government regulation or memoranda of understanding with industry. Safety requirements can take the form of content oriented or process oriented requirements. Content oriented requirements prescribe test protocols and compare measured values against a pre-established criteria. Process oriented requirements specify system design and development processes to ensure that relevant safety issues have been considered. Process oriented requirements can also address organizational safety management practice, including core competencies of safety professionals, development of product safety information, and guidelines for auditing of the safety system.

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<sup>2</sup> Various systems should be evaluated together when they can co-exist in a vehicle. For example, separate systems for adaptive cruise control and forward collision obstacle detection may produce redundant or conflicting messages. A full appreciation for the interactions of such systems can only be gained by concurrent evaluation.

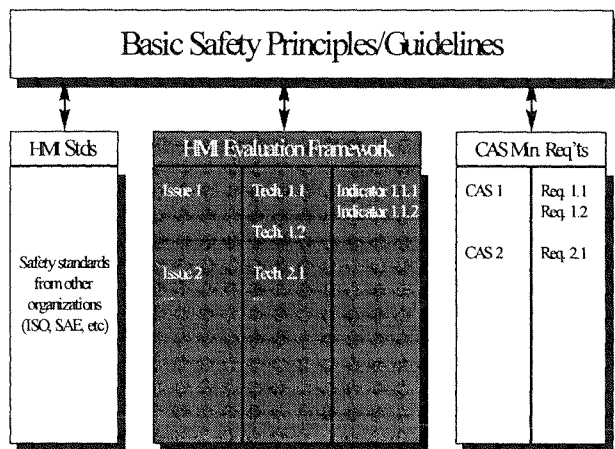


Figure 1. Principal Elements of ITS Safety Assurance.

### Basic Safety Principles/Guidelines

The basic safety principles/guidelines provide general, widely-accepted design and operational information to promote system compatibility with known driver characteristics. The European Code of Practice on Human Machine Interface for In-Vehicle Information and Communication Systems and the Draft British Standards Institute Guide to In-Vehicle Information Systems are examples of basic design guidelines. The guidelines in this category, however, are very general. For example, they may state that functions or display modes that overload the driver or intrude on the driving task should be disabled while driving, but they do not specify the functions or modes or indicate what constitutes overload or intrusion. To augment these basic guidelines, human factors engineering principles (e.g., stimulus-response compatibility) are available from standard references.

### Human-Machine Interface (HMI) standards

Another important element in the model concerns automotive human-machine interface (HMI) standards such as the design of visual and auditory displays. HMI is defined broadly and includes design aspects such as system functionality, message prioritization in addition to the physical characteristics of the interface. Several standards bodies (e.g., ISO, SAE,) are working to develop industry standards for HMI with a view towards providing an ergonomically sound interface that is compatible with driver needs, capacities and limitations. Standardization of HMI elements facilitates drivers' understanding of system function and ensure consistency of operation.

Relevant HMI standards are developed primarily by ISO/TC22/SC13/WG8. However, other groups also

develop HMI-related standards. The standards or work items currently under development within WG8 include:

- Visual Presentation of Information
- Auditory Information Presentation
- Dialogue Management
- Measurement of Driver Visual Behaviour
- Priority of TICS      Suitability of TICS for Use While Driving
- Comprehensible Presentation of Visual Messages
- Audible Symbols
- ACC Systems - MMI Requirements

Standards pertaining to ITS-related visual symbols are being developed by WG5.

Relevant standards under development within ISO/TC204/WG 14 include:

- Mayday Systems
- Adaptive Cruise Control

Relevant standards under development within SAE ITS Human Factors and Safety Committee include:

- Navigation Function Accessibility
- Navigation MMI
- ACC MMI and Operating Characteristics
- Message Priority

### Collision Avoidance Systems Minimum Requirements

Collision avoidance systems are systems that detect hazardous conditions and either warn the driver or trigger an automatic avoidance manoeuvre such as braking. The distinction between collision avoidance systems and other types of ITS is often not clear. For example, an adaptive cruise control is normally described as a convenience feature, especially if deceleration is limited to that available from engine power. If the same system also warns the driver of a forward obstacle it may be referred to as a forward obstacle warning system and if that system is capable of initiative braking it is a collision avoidance system.

Collision avoidance systems present a formidable challenge to designers because of the necessity to provide the driver a clear message in a short period of time in such a way as to be non-startling and without risk of causing inappropriate response. Because collision avoidance systems intervene in situations where the risk of collision is moderate or high, it is important to establish minimum functional requirements. Several groups are working to develop minimum requirements for specific CAS. However, no standard or guideline presently exists to help designers select appropriate functional characteristics to maximize safety benefits.

Relevant standards under development within ISO/TC204/WG 14 include:

- Forward Obstacle Warning System
- Traffic Impediment Warning System
- Maneuvering Aid for Low Speed Operation
- Lane Departure Warning System

Relevant standards under development within SAE ITS Human Factors and Safety Committee include:

- Forward Obstacle Warning MMI and Operating Characteristics
- Side Obstacle Warning Backup Warning

Other collision avoidance systems not being addressed include driver condition warning, and intersection collision avoidance.

### Human-Machine Interaction Evaluation Framework

Existing guidelines, HMI standards, or minimum functional requirements for CAS, do not adequately address the safety assurance requirements of ITS for which the underlying technologies and functionality are constantly changing. Technology is advancing more rapidly than the scientific knowledge about its effects on driver performance and behaviour. For this reason, there will likely be an increasing need for prospective techniques for evaluating the safety of on-board systems in the development and certification of ITS vehicles. Questions about what issues need to be addressed in these evaluations, how to investigate them and what criteria define acceptable performance constitute the subject matter for collaborative research.

The development of the framework for evaluation of ITS systems represents the core work of the IHRA-ITS WG. An initial outline of the framework is presented in Figure 2. The details are to be developed through consolidation of scientific knowledge and further research.

The framework contains both direct measures of safety as well intervening behavioural mechanisms. Direct Safety Effects refers to measured outcomes in terms of safety, including collision or incident frequency, conflicts and safety-critical errors. Three main mechanisms are identified by which on-board information, control or communication systems can influence safety; behavioural adaptation, workload, and usability. Behavioural adaptation refers to behaviours which may occur following the introduction of changes to the road-vehicle-user system and which were not intended by the initiators of the change<sup>1</sup>. Workload refers to the portion of the driver's maximum mental resource capacity expended in the performance of the driving task. Usability refers to the extent to which a system or device is effective, efficient, satisfying, easy to learn and control, and is compatible with task goals in the driving environment.

Evaluations should address each of these broad areas to ensure that system design and integration is safe and compatible with the driving task. For each safety mechanism, techniques will be identified that can be used to assess the adequacy of system safety performance. Safety indicators, or measures believed to be relevant to safety will be specified for each technique indicated. Since it is unlikely that absolute safety performance criteria can be established in the foreseeable future, the techniques may

Safety Mechanism	Conditions		Technique	Indicators/Benchmarks
	Driver	Driving		
Direct Safety Effects (e.g., conflicts, incidences)				
Behavioural Adaptation				
Workload (e.g., visual demand, distraction)				
Usability (e.g., errors, time)				

Figure 2. ITS Evaluation Framework.

<sup>1</sup> OECD Scientific Expert Group, "Behavioural adaptation to changes in the road transport system". 1990, Paris: OECD.

take the form of comparative evaluations in which the subject system is compared against a benchmark. Benchmarks are reference levels of performance that are considered to be acceptable from a safety perspective. They might, for example, indicate baseline levels of performance (e.g., without the ITS). The driver and driving conditions to be represented in the evaluations are the same for all safety mechanisms.

Expert groups will be formed to identify further research needs and opportunities associated with elaborating the framework. To start the process, recognized experts in each of the four principal safety mechanisms, as identified in the table, would be asked to prepare a brief summary of the current state-of-the-art in their selected area. This would be followed by the formation of expert groups which would organize separate workshops in each area with the specific aim of summarizing current knowledge and formulating research recommendations. A fifth expert group would then consider what driving tasks and driving conditions should be incorporated in the summative evaluations.

## RECENT WG ACTIVITIES

### Workshop

An ITS Safety Test and Evaluation workshop was held in conjunction with the Third ITS World Congress in Berlin, October, 1997. There were many good presentations covering a broad range of evaluation techniques - too many, in fact, for in-depth discussion. Some of the techniques presented are summarized below. Many important aspects of evaluation were raised that are not immediately apparent. For example, the need to consider the impact on non-equipped vehicles and the influence of driving style on test results are important considerations in the evaluation of safety.

Several European projects have attempted to address this topic, with limited success due to lack of continued funding. Specifically, Drive II projects (HOPES, HARDIE, EMMIS, and GEM) attempted to prepare frameworks, guidelines, and methodologies for safety assessment of in-vehicle systems. They collected a lot of data and developed, manuals, databases, and tools such as Skill Acquisition Network (SANE) and Dialogue Design and Evaluation Method (DIADEM). However, the results of these efforts have not addressed safety specifically, they lack full scale context and employ too many measurements. Continuation of these types of studies have not been supported by European Commission (EC).

## SUMMARY OF TECHNIQUES PRESENTED

1. Usability testing using field operational tests, including de-briefings and focus groups (ref: UMTRI ACC study, J. Sayer). A feature of the data acquisition system was identification of events of interest (e.g., lane change) and capture of video data prior to and following events. The importance of collecting baseline data by individual parameters (e.g., age) was emphasized.
2. Field operational tests (ref: PSA Peugeot Citroen study of ICC, Florence Nathan). Collected engineering data in addition to human factors data, to facilitate communication with designers. Raised the issue of effects on drivers of non-equipped vehicles and other road users. Also indicated the need to include individual difference parameters such as driving style.
3. Open-road evaluation using behavioural and verbal protocol analysis to obtain insight into driver strategic behaviours (ref: INRETS/Renault study, F. Saad). Researchers analyzed general behavioural data as well as specific lane change manoeuvres. Concluded that drivers of ACC-equipped vehicles tend to exhibit fewer manoeuvres and greater left lane driving. Also showed an overall reduction of time headway with ACC. However, when performing lane change manoeuvres, time headway depended on traffic conditions (higher with ACC under lighter traffic and higher when pulling out to pass with ACC). Concluded that situational variables and driving style are important factors. Simulation for prospective evaluation of safety (ref: Lena Nilsson). A major point raised was the need to look at the individual road user as well as effects on traffic and society (as filtered through the traffic system). However, we do not have an adequate understanding of safety and therefore must rely on surrogate measures.
4. Computer-based checklist (ref: Karel Brookhuis). The development of a relatively quick prospective assessment of IVIS was described. This is still under development in the Netherlands.
5. Secondary task methodology to assess mental demand in laboratory and in the field (ref: University of Cologne, Hering).
6. Combination of techniques to address a comprehensive evaluation of the issues (ref: Tijerina) during CAS development. A framework for evaluating lane change crash avoidance systems was presented as an example. The framework consists of a series of questions to be considered during evaluation and indicates the possible methods that might be applied to address these



questions. A comprehensive evaluation should address at least the following questions:

- Does the CAS address driving conditions related to crash involvement?
- Does the CAS logic support driver's decision making tasks?
- Is the CAS display location compatible with normal driver behaviour?
- Does the CAS match the driver's sensory characteristics?
- Is the CAS display content meaningful to the driver?
- Does the CAS have any unintended negative safety consequences?
- Does the CAS reduce crash incidence or severity?

## OTHER INFORMATION

Ford and GM have established a program of collaborative research, Crash Avoidance Metrics Partnership (CAMP), to accelerate development of ITS countermeasures by pre-competitive assessment of the need, feasibility and marketability. Current area of interest is rear-end collision countermeasures, including development of relevant scenarios, functional requirements and test methodology.

NHTSA's current research is focused in three categories: projects related to specific collision types (rear-end, road departure, lane change and merge, heavy vehicle stability, intersections), driver performance (driver status monitoring, vision enhancement, human-vehicle interaction), and post-collision injury mitigation. The Intelligent Vehicle Initiative (IVI) developed to facilitate product deployment, includes development of services (autonomous and cooperative), selection of services for integration, integrated system design and development, operational tests and evaluation.

## Literature Database

The WG is in the process of developing a database of research relevant to ITS safety test and evaluation. The database will include work either on-going or completed in the last five years that may be relevant to the development of procedures that can be used to assess the safety of on-board information, control and communication systems with respect to human performance and behaviour. The techniques may include measures of performance, workload assessment, usability, situation awareness, protocol analysis, etc. A survey form was developed and distributed to WG members for completion. The database will be updated on an on-going basis.

## RELATIONS WITH OTHER GROUPS

A number of related activities have taken place recently involving other groups. For example, a proposal to amend the ECE Consolidated Resolution on the Construction of Vehicles (R.E. 3) to include new "Guidelines for the Design and Installation of Information and Communication Systems in Motor Vehicles" was submitted to WP29 by German Experts. WP 29 deferred discussion on this proposal until June 1998. The European Commission has adopted a "Code of Practice on HMI for In-Vehicle Information and Communication Systems". In addition, the EC DGX111 High Level Group on Telematics has developed a draft report, "Telematics and Intelligent Transport Applications for Road Safety". In addition, guidelines are under development in Japan and Europe addressing the safety considerations related to ITS.

The WG is in the process of establishing liaison with other groups, including;

- European Commission, Directorate-General XIII/C/6
- European Commission, Directorate-General VII
- OECD
- APEC- Special Interest Group on ITS
- INRETS: Programme de recherche et développement des industries en transport (PREDIT )
- Organisation Internationale des Constructeurs d'Automobiles (OICA)
- Comité de Liaison de la Construction d'Equipements et Pièces pour Automobiles (CLEPA)
- UNECE Working Party 29
- European Union High Level Group on Road Safety
- European Union High Level Group on Telematics
- ACEA/EUCAR Telematics Working Group 'H'
- ERTICO
- ITS America
- VERTIS Office
- JAMA
- AAMA
- US Car
- ISOTC22/WG 8
- ISO/TC204
- ISO/TC204/WG14
- Joint HLG Task Force
- CEN TC 278
- PIARC Committee C16
- PIARC Committee C13 WG6
- FCAT (Australia)
- FAIM (Australia)
- ITS Australia
- ITS Canada
- SAE ITS Safety and Human Factors Committee
- Canadian Vehicle Manufacturers' Association (CVMA)

- Association of International Automobile Manufacturers of Canada (AIAMC)
- EU-working party "Telematics and Intelligent Transport Applications for Road Safety"

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## PROMOTION PLAN OF THE DEVELOPMENT OF ADVANCED SAFETY VEHICLE (ASV)

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### SUMMARY

The Ministry of Transport has established the "Study Group for Promotion of Advanced Safety Vehicle (ASV)" consisting of several university professors and manufacturers and has conducted research & development of ASVs equipped with numerous driver-friendly devices to ensure high-level safety by applying advanced electronics technology.

### BACKGROUND OF THE PLAN FOR PROMOTING DEVELOPMENT OF THE "ADVANCED SAFETY VEHICLE"

The automotive society has given birth to such problems as increased traffic accidents and traffic congestion, which need resolution. Particularly in the area of traffic accidents, the number of traffic fatalities in Japan for the year 1996, at 9,942, dropped to just barely below 10,000 persons for the first time in 9 years, however we are still in a undesirable situation. One method which the Ministry of Transport has been thinking of to respond to this drastic traffic accident problem is improvement of the automobile, to make highly intelligent vehicles through the utilization of new technologies such as electronics technologies which have been advancing rapidly in recent years, and research and development into the ASV (Fig. 1) to raise the level of safety overall. The ASV would also become the platform as the vehicle used for Intelligent Transport Systems (ITS). To accomplish this, the Ministry of Transport enlisted the participation of university researchers related to automotive technologies, Japanese automobile and motorcycle manufacturers (First Period: 9 Companies; Second Period: 13 Companies) and research organizations, etc. related to the automobile and established the "Study Group for Promotion of Advanced

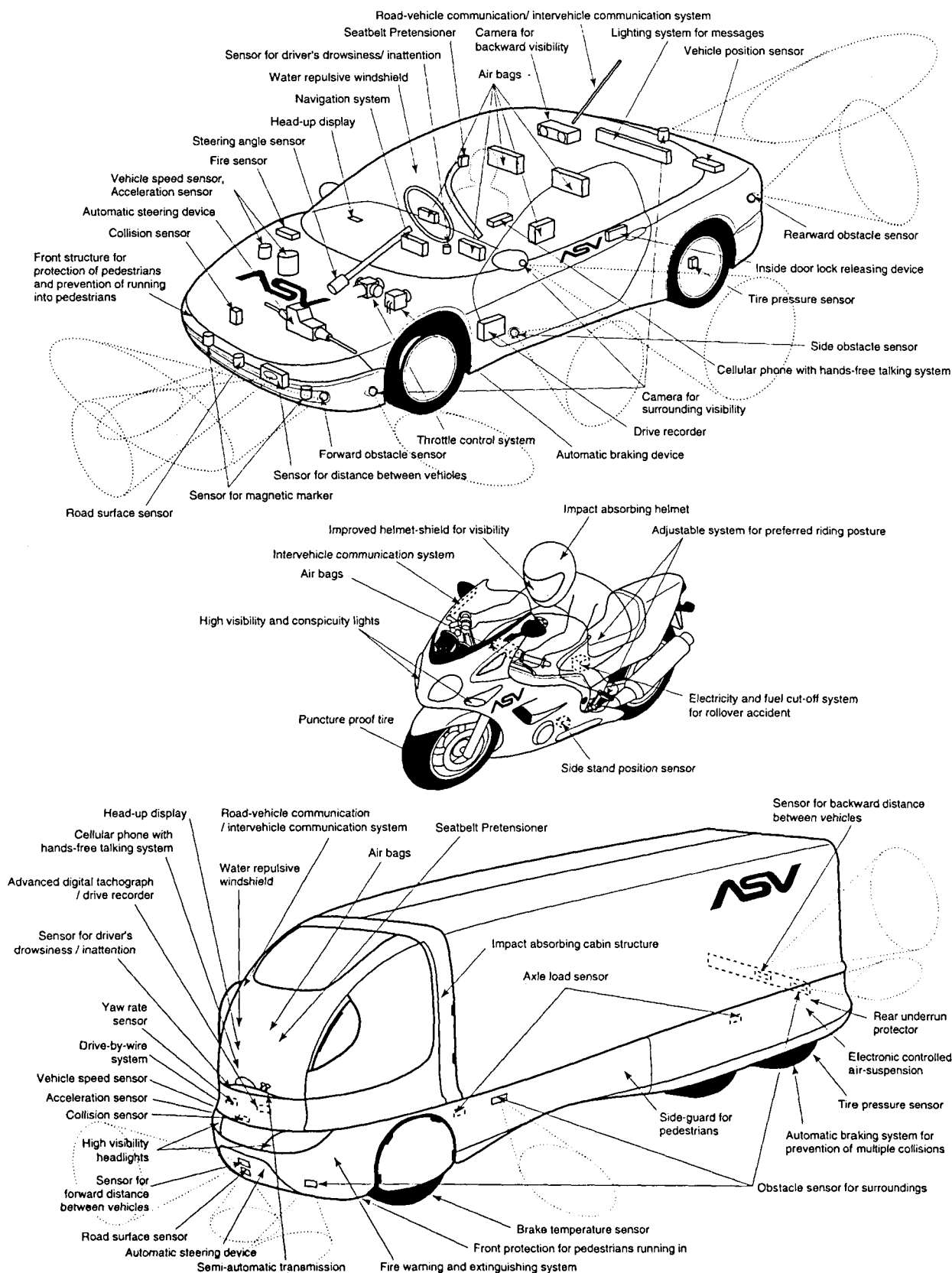
Safety Vehicle (ASV)" (Chairman: Masakazu Iguchi, Emeritus Professor of Tokyo University; Administration: the Ministry of Transport, Engineering and Safety Department).

The aim of the ASV plan is to equip vehicles with sensors which detect the surrounding traffic environment as well as road surface conditions and with information and communication processing equipment for accident avoidance, and to conduct research into advanced technologies for automatic braking systems and automatic steering systems necessary for lessening the damage resulting from collisions, and then, by pointing out technological guidelines for the ideal ASV of the future, ASV is to attempt to promote higher levels of research and development of automotive safety technologies among the people (automobile and motorcycle manufacturers). In addition, ASV research and development is not being financed by government funding, in any way, in view of the importance of preserving the independence of private enterprise.

### FIRST PERIOD-OUTLINE OF THE ASV DEVELOPMENT PROMOTION PLAN

Study Group for Promotion of ASV and ASV Research and Development Maker Activities

In the first period between 1991 and 1995, the Study Group for Promotion of ASV set 4 fields of major safety technologies, (1) preventive safety technologies, (2) accident avoidance technologies, (3) damage decreasing technologies and (4) post-impact injury mitigation and prevention technologies, and carried on investigative research into methods of these four major safety technologies, and ascertaining the effects, of introducing these ASV technologies on accident reduction. Furthermore, together with the



(Fig 1. Image of ASV)

fruits of the above investigation, the opinions of manufacturers, etc. involved in ASV research and development were concentrated and a policy for ASV technologies was developed. In addition, each of the ASV research and development manufacturers was engaged in research on the various factors involved, systems research, and in fundamental research, to make technologies practical as well as research and development of ASV element technologies. Then 16 prototype vehicles were manufactured by the various companies in which most of the ASV element technologies were incorporated.

### **Research and Development Conditions of Systems Technologies in the 4 Fields**

Under the above mentioned 4 fields of major safety technology, 20 systems technology items were decided upon and research and development was promoted. Here we will introduce some representative examples from 3 of these fields.

#### **Preventive Safety Technologies (Example of Drowsy Driving Warning System)**

##### **Objective**

The purpose of this technology is to detect driver drowsiness (reduced awareness) and not only awake the driver corresponding to his drowsy state but stop the vehicle automatically if the driver is in a condition where he cannot drive, and thus attempt to reduce accidents.

##### **System Functions**

(1) Driver Drowsiness Detection Function: There are two methods for detecting if the driver is drowsy, by detecting the vehicle's running state, or by detecting the driver's physiological condition. The former utilizes a steering wheel angle sensor, CCD camera, yaw rate sensor and other instruments. On the other hand, the latter utilizes a pulse sensor, a CCD camera to monitor the driver's eye movements and similar sensors.

(2) Drowsy Driving Prevention Function: The method used to judge whether the driver is in the drowsy state is to process the signals detected by the various types of drowsiness sensor with a computer, which would judge that the driver is in the drowsy state when the observed values exceed the proper threshold level.

In addition, the driver could be awakened by showing something on a display, a warning sound, a voice, vibrating the seat, or by releasing a menthol scent, etc. Furthermore, if the driver continues in a dangerous condition even after being warned, the vehicle could be halted by automatic braking, while steering itself automatically and while flashing the

hazard warning lamps to caution other drivers.

##### **Results**

It was determined that when a driver lapses into a drowsy state, the steering correction period becomes long, and changes in the heart beat interval become broader. In addition, it was confirmed that the drowsiness detection accuracy differs depending on individual differences.

##### **Future Themes**

It is necessary to improve detection technologies and technologies for awaking drowsy drivers, and to study automatic avoidance technologies.

#### **Accident Avoidance Technologies (Example of Automatic Operating System for Avoiding Accidents)**

##### **Objective**

To monitor objects in the area surrounding the vehicle (other vehicles, pedestrians, road structures, etc.) and, if there is danger of a collision, first warn the driver, then, if the driver doesn't take the appropriate action, carry out automatic braking or automatic steering to reduce accidents.

##### **System Functions**

(1) Recognition of the driving environment around the vehicle: Scanning type laser radar, mili-wave radar, CCD cameras, are methods used.

(2) Alerting the Driver to the Danger of Collision: This is done using a head up display (HUD) which portrays the positional relationships of the driver's own vehicle to objects surrounding it in easy to understand pictures, and sound and display are used together to warn when the situation becomes dangerous.

(3) Emergency Collision Avoidance Functions: If the driver's response is delayed and it is judged that it is difficult to avoid a collision, it is proposed that the most appropriate avoidance action will be taken using automatic braking or automatic steering.

##### **Results**

The functions of systems focused on avoiding accidents involving other vehicles or pedestrians in cases where the driver is incapacitated, as well as the functions of systems which apply the brakes automatically to reduce speed as much as possible in cases where a collision cannot be avoided, and systems which avoid collisions by automatic steering in addition to automatic braking were confirmed.

##### **Future Themes**

It is necessary to improve the reliability of automatic steering, study interference between automatic braking and driver operation, establish a method for canceling automatic braking, clarify automatic braking system operating conditions and form

a consensus in society that automatic operation is a means of assisting in avoiding accidents.

#### **Damage Decreasing Technologies (Example of a Pedestrian Injury Severity Reduction System)**

##### **Objective**

The purpose of this research and development is to reduce the number of accidents involving pedestrians through countermeasures to decrease the severity of injury to pedestrians when there is an impact. Furthermore, although this item is classified as "damage decreasing technologies", it includes accident prevention technologies which are geared to protection of pedestrians.

##### **System Functions**

###### **(1) Functions for Prevention of Hitting Pedestrians:**

This system would use scanning laser radar to detect pedestrians and would warn the driver using an indication in HUD and a warning sound or voice, then if the danger becomes greater, operate the brakes automatically. At night, it would detect infrared rays radiated from pedestrians and improve the visibility of pedestrians, without causing an illusion for vehicles approaching in the opposite direction, then with ultrasonic sensors it would detect pedestrians who are crossing the street and warn the driver that there is danger of hitting someone by showing a warning in the HUD or by a warning sound and voice, making it possible to take evasive action.

**(2) Functions to Reduce the Severity of Injury to Pedestrians:** When an impact with a pedestrian is detected by the pedestrian impact sensor, an airbag mounted in the hood could work, reducing the severity of injury to the pedestrian's head. In order to reduce the severity of injury to a pedestrian, the bumper, hood front end, the hood itself and front pillars use impact absorbing construction.

##### **Results**

It was determined that, by making high performance scanning laser radar, it is possible to detect a pedestrian wearing clothing which is difficult to see at night (with a detection distance of 45 meters or greater), and that through the development of recognition logic with the features of pedestrian behavior incorporated into it, pedestrians who cross the roadway should be recognizable. In addition, it was confirmed that the severity of head injuries is reduced for impacts where a hood airbag is operated in the area of the pedestrian's head and that the severity of limb can be reduced by impact absorbing bumpers.

##### **Future Themes**

It is necessary to meet problems with mutually

interfering ultrasonic waves in systems which employ ultrasonic sensors, and to distinguish infrared radiation from objects other than the human body as well as prevent malfunction due to emitted or reflected infrared radiation. Also, it is necessary to establish legal permission concerning the freedom to switch on lights for a pedestrian lighting system.

#### **Technology Guidelines**

##### **Establishing Technology Guidelines**

Technology guidelines were conceptualized in the form of a target "Position After 5 Years" and "Ideal Position after 10 Years," after taking into consideration the likelihood of success in making these systems practical in the 4 fields (1) preventive safety technologies, (2) accident avoidance technologies, (3) damage decreasing technologies and (4) post-impact injury mitigation and prevention technologies, by clarifying the development conditions for safety technologies up to the present and the research results, and by further clarification of future technological themes and various themes other than the vehicle itself, then, by considering these themes overall, with the purpose of showing the directivity of technological developments aimed at the 21st century.

The accident reduction effects shown here are the anticipation reduction with respect to the total number of traffic related fatalities in mid-1993 (4,846). This accident reduction effect is the maximum value that can be expected if the current fatal accident occurrence conditions do not change in the future, if all the vehicles on the road are equipped with ASV technologies, and supposing that all the necessary infrastructure is in place. However, if we simply total up the anticipated reduction in fatalities for each system, the effects multiply and the results become overly large, so it is necessary to look at the results for each system only.

##### **Technology Guidelines for Preventive Safety Technologies**

**(Using the Drowsy Driving Warning System as an Example)**

###### **Target Position**

The "Position after 5 Years" for this system is to detect a drop in the driver's awareness under specific conditions, and to give an alarm as well as apply stimulation to awaken the driver. The "Ideal Position after 10 Years" is to detect a drop in the driver's awareness under various conditions, give the optimum level of alarm, apply stimulation, and then, if the dangerous condition continues, stop the vehicle automatically while giving careful attention to

surrounding vehicles.

#### **Vehicle Related Technology Themes**

It is desirable to establish the methods of detection which won't be a nuisance to the driver or cause feelings of disorder, and to establish judgment methods, which take individual differences into account. Also, the overriding themes should be assuring system reliability and durability, miniaturization of components and reduction of system costs. (This theme is a common item in each system other than this system.)

#### **Themes Other than Vehicle Related Themes**

It is desirable that a road environment with easily recognizable lane markings be provided and that long distance night driving be monitored.

#### **Accident Reduction Effects**

It is expected that the reduction in fatal accidents could be up to 330 lives per year.

#### **Technology Guidelines for Accident Avoidance Technology**

(Using the Accident Avoidance Automatic Driving System as an Example)

#### **Target Position**

The "Position after 5 Years" for this system, is that it will be capable of detecting the driving environment and, if there is a great danger rear-end collision with the vehicle ahead, the overtaking speed would be reduced by automatic control. Also, the "Ideal Position after 10 Years" it is desirable that, through integration with road surface prediction and steering avoidance technologies, it become possible to achieve automatic accident avoidance under various circumstances.

#### **Vehicle Related Technology Themes**

It is desirable that the recognition power for surroundings under bad conditions such as curves and hilly roads be improved, that the performance of pedestrian recognition logic be improved and that technologies for monitoring surroundings under various conditions be improved. It is also necessary to predict and respond to other dangers which may occur due to automatic avoidance and verify the effectiveness of the system under various conditions.

#### **Themes Other than Vehicle Related Themes**

Provision of a road environment with easily recognizable lane markings, road markers and other infrastructure are very important. Furthermore, it is desirable to standardize the installation and setting methods for roadside reflectors, and to establish vehicle to road communication systems for accident avoidance.

#### **Accident Reduction Effect**

It is predicted that the fatal accident reduction effect per year will be up to 2,192 persons, with the effect maximized in the First Period of ASV system use.

#### **Technology Guidance for Damage Decreasing Technologies**

(Using the Pedestrian Injury Severity Reduction System as an Example)

#### **Target Position**

The "Position after 5 Years" for this system is that, under specific conditions, pedestrians in front of the vehicle will be detected, and, if it is estimated that there is danger of hitting any person, the driver will be warned that he or she is there. As for the "Ideal Position after 10 Years" it is desirable that, if the danger of an impact becomes even greater, it will be possible to apply the brakes automatically under specific conditions.

#### **Vehicle Related Technology Themes**

Concerning detection of pedestrians, it is essential that detection technologies, and monitoring and recognition technologies, be improved so that there will be no miss-detection and non-detection of pedestrians.

#### **Themes Other than Vehicle Related Themes**

In order to reduce accidents involving pedestrians, it is desirable that facilities be provided to separate pedestrian lanes from traffic lanes. It is also necessary that all drivers become more knowledgeable of the importance of protecting the weak and defenseless pedestrians.

#### **Accident Reduction Effect**

It is predicted that the annual reduction in fatal accidents will be up to 570 persons.

## **SECOND PERIOD-OUTLINE OF THE ASV DEVELOPMENT PROMOTION PLAN**

### **Expansion of the Promotion System and Affected Vehicle Models**

The Second Period Advanced Safety Vehicle (ASV) Promotion and Investigation Group, organized for the five-year period beginning in 1996 and composed of men of learning and experience, automobile manufacturers and related government authorities undertook, in addition to research and development concerning element technologies begun in the First Period, optimization of the human interface indicated as a future investigation theme, and its integration with and linkage to the ITS and other

infrastructure, as well as the promotions among private citizens to facilitate research and development of automotive safety technologies. Expanding the types of vehicle model, trucks, buses and motorcycles have been added as objects of ASV research and development.

In accordance with this change, the number of manufacturers engaged in ASV research and development has been in total 13.

### Adjustment of ASV Research and Development

In the year 1996, ASV research and development conditions were adjusted, and the current conditions of research and development related to the human interface and current infrastructure conditions were investigated.

#### 6 Fields of Major Safety Technology

As a result of the readjustment, 6 major safety technology fields were set, (1) Preventive Safety Technologies, (2) Accident Avoidance Technologies, (3) Autonomous Driving Technologies, (4) Damage Decreasing Technologies, (5) Post-impact Injury Mitigation and Prevention Technologies and (6) Fundamental Automotive Engineering Technologies, then from these fields, 32 system technologies were classified and introduced into ASV research and development items. Detailed element technologies identified in System Technologies totaled 107 items as of April, 1997.

In the future, in Second Period ASV plans, research and development are being promoted with the objective of gradually introducing each of the ASV system technologies by incorporating them into vehicles in the marketplace within the period remaining of this century, and of developing a system which can carry out integrated control of these system technologies.

Along with the stream, as the 21st Century begins, the aim is to make ASV vehicles equipped with the integrated system available to everyone.

#### The 32 Systems Technologies

##### (1) Preventive Safety Technologies

- 1 Warning System for Dangerous Driver Conditions
- 2 Warning System for Dangerous Vehicle Conditions
- 3 Vision Enhancement System
- 4 Vision Enhancement System in Nighttime Driving and Nighttime Object Detection
- 5 Blind Area Monitoring/Warning System
- 6 Surroundings Warning System
- 7 Road Environment Information Acquisition and Warning System
- 8 Inter-vehicle Communication and Warning

#### System

- 9 Driver Workload Reduction System
- (2) Accident Avoidance Technologies
  - 10 Intelligent Vehicle Control System
  - 11 Driver's Hazardous Condition Detection System
  - 12 Blind Area Accident Avoidance System
  - 13 Collision Avoidance System with Surrounding Obstacles
  - 14 Collision Avoidance System Utilizing Road Information
- (3) Autonomous Driving Technologies
  - 15 Autonomous Driving System Utilizing the Existing Infrastructure
  - 16 Autonomous Driving System Utilizing Newly Installed Infrastructure
- (4) Damage Decreasing Technologies
  - 17 Impact Absorbing System
  - 18 Occupant Protection System
  - 19 Pedestrian Injury Severity Reduction System
- (5) Post-impact Injury Mitigation and Prevention Technologies
  - 20 Emergency Door Lock Release System
  - 21 Secondary Impact Reduction System
  - 22 Fire Extinguishing System
  - 23 Automatic Emergency Reporting System
- (6) Fundamental Automotive Engineering Technologies
  - 24 Safer Usage System of Cellular Phone
  - 25 Advanced Digital Tachometer/Drive Recorder
  - 26 Electronic Vehicle Identification Tag (Number)
  - 27 Automatic Reporting System of Vehicle Condition
  - 28 Advanced Global Positioning System
  - 29 Drive-by-wire System
  - 30 Advanced System for Elderly Drivers
  - 31 Physiological Detection System for Fatigued Drivers
  - 32 Advanced Human Interface System

#### Future Investigation Themes, etc.

##### Optimization of Human Interface

Problems with the human interface include how to transfer information detected by each sensor, and how to carry out the various types of automatic control without causing feelings of disorder in the driver. It is necessary to transfer the required information unflinching in an easy form to understand, and it is feared that as information increases, it will be difficult to judge appropriately and that the driver will get tired from repeated warnings. In addition, concerning control, there is the problem that what kind of control would be desirable in response to the surrounding



environment and the driver's operations.

As for information transfer and control methods, at present, there are differences depending on the manufacturer, so that consideration is given to the study of standardization in the ISO activity. There also needs to be study of the necessity for standardization of methods for warning, timing and automatic control, etc.

#### **Integration with and Linkage to Infrastructure**

Concerning the themes of integration with and linkage to the infrastructure, there are problems with which methods to use to transfer information from the infrastructure, such as road conditions and traffic signals and information from the vehicle. If it is possible to obtain information on the occurrence of an accident or a traffic jam up ahead through a vehicle-to-road communications system, it can be expected that safety will improve, so there should be study on the technologies for such a system.

Concerning autonomous driving system vehicles, studies should be divided between independent autonomous driving systems and autonomous driving systems which utilize newly installed infrastructure such as magnetic nails.

## PILOT STUDY OF ACCIDENT SCENARIOS ON A DRIVING SIMULATOR

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### ABSTRACT

This paper presents a pilot experimental study carried out by the Laboratory of Accidentology and Biomechanics PSA Peugeot Citroën - RENAULT (LAB) and the European Center of Safety Studies and Risk Analysis (CEESAR) on the RENAULT ESTER motionless driving simulator. Sixty-eight drivers were exposed to a dangerous situation in which another car failed to stop at an intersection. Three distinct configurations were tested : vehicle coming from the right either at a constant speed or decelerating, or stationary vehicle moving-off from the left. Kinematic data and a video presenting the driver's face and the field of view were recorded. After the driving session, drivers were interviewed by a psychologist of in-depth accident investigation teams in order to analyze their interpretation of the situation.

The analysis carried out is based on a comparison of the behavior (perceptions, interpretations, actions) of drivers who avoided the accident with the behavior of those who crashed. It points out different kinds of difficulties according to the configuration : problems of perception (angular limitations), anticipation (no anticipation of the possible motion of the adverse vehicle) or interpretation (incorrect estimation of the danger level). It provides a basis for the determination of avoidance strategies and the design of active crash avoidance systems (intelligent collision avoidance systems as well as active braking boosters) with the specification (triggering threshold) and efficiency assessment of such systems. This study also provides data for accident reconstruction (e.g. reaction time in accident situations, motion perception threshold...).

### INTRODUCTION

Studies conducted on the limits of secondary safety have proved that approximately half of car occupants fatally injured in car accidents could be saved only by

means of primary safety (Thomas 1990). In order to provide better safety, car manufacturers are developing crash avoidance systems. Beyond general accident statistics, the specification of such systems requires accurate data on the space and time history of accidents : vehicles' positions, speeds, accelerations and drivers' actions on the accelerator, brake pedal and steering wheel.

General accident databases enable a determination of the most frequent accident situations in which active systems must operate. For example, an analysis conducted on personal injury accidents in France from 1993 to 1995, points out that among accidents involving at least one passenger car :

- 36 % occur at intersections,
- 49 % of two-vehicle accidents occur at intersections,
- 67 % of front-to-side collisions occur at intersections.

These figures, combined with the fact that passive safety systems have a more limited potential efficiency in front-to-side collisions, highlight that intersection accidents are very relevant in the field of active safety. A more detailed analysis carried out on a one year fatal accident report database (a description of this database is provided by Thomas 1996) shows that, among intersection accidents in which at least one car occupant was fatally injured :

- 70 % occur outside urban areas,
- 72 % occur in the daytime,
- 84 % occur on a dry road,
- 91 % occur without any visibility mask,
- 77 % of non-right-of-way are sign posted,
- more than 80 % of drivers were crossing straight.

In-depth accident studies with full accident reconstruction provide much more thorough data on the space and time history of accidents (Damville 1997). Reconstructions may be useful to specify some crash avoidance systems, such as emergency braking dynamic assistance or automatic braking anti-collision systems (Perron 1997). Despite the fact that those studies give data on real world accidents, they lack sufficient accuracy, especially concerning drivers' actions.

In this context, driving simulator experiments seem to be well suited to the analysis of driver behavior in accident situations and complementary to in-depth accident studies. At a methodological level, the aim of the pilot study presented hereafter is to analyze the potential of a motionless driving simulator in certain accident situations for the analysis of driver behavior and the specification of crash avoidance systems. At a more operational level, the experiment is aimed at analyzing the avoidance strategies of right-of-way drivers at intersections when another vehicle fails to yield, in order to determine how to improve them by means of crash avoidance systems (a full analysis of this experiment is provided by Perron 1997).

## MATERIAL AND METHOD

**Driving Simulator** - The experiment was conducted on the ESTER fixed-base driving simulator developed by RENAULT Research Department (Chevennement 1997, Morel Guillemaz 1997). The mock-up is a full RENAULT 19 with a steering wheel actuator. It is not fitted with an Anti-lock Braking System. The visual field covers the entire windshield (from 30° on the left to 50° on the right, figure 1). Engine and aerodynamic noise are simulated by using sampling technology.

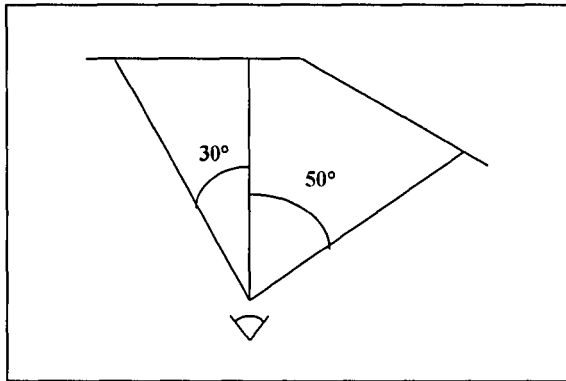


Figure 1. Field of view of the driving simulator.

**Configurations** - The experimental conditions tested in this experiment were chosen according to the macro-accidentologic data presented above :

- the intersection is located in rural area,
- the non-right-of-way vehicle comes from a road perpendicular to the driver,
- the weather conditions are good (daylight, dry road),
- there is no visibility mask,
- the intersection is fully sign posted.

The kinematic configurations of the non-right-of-way vehicle were determined on the basis of in-depth accident studies with full kinematic reconstruction. The non-right-of-way vehicle is hereafter called the "adverse vehicle". These configurations were also defined in accordance with the simulator specificity. In each configuration, the adverse vehicle is given a certain kinematic law which is triggered when the estimated time to the intersection of drivers reaches a certain value. This time-to-intersection is computed on the basis of a constant speed of the driver. The choice of the adverse vehicle's kinematics and time-to-intersection trigger are combined in order to place the adverse vehicle in the middle of the driver's lane when crossing the intersection (supposing that the driver keeps a constant speed). Three main configurations were defined (a pictogram of each configuration is given in figure 2) :

- In configuration 0, the adverse vehicle arrives at the intersection from the driver's right, at a constant speed of 60 km/h. It is triggered and immediately visible 6.10 s before the driver arrives at the intersection (supposing that he keeps a constant speed).
- In configuration 1, the adverse vehicle arrives at the intersection from the driver's right, decelerating from 80 to 30 km/h at  $3 \text{ m/s}^2$ . At 10 m from the intersection, the vehicle maintains its speed at 30 km/h, and accelerates at  $1 \text{ m/s}^2$  when arriving in the middle of the junction. It is triggered and immediately visible 6.10 s before the driver arrives at the intersection (supposing that he keeps a constant speed).
- In configuration 2, the adverse vehicle is stopped and visible 1 m behind the stop line, on the left of the driver. It moves off 3.25 s before the driver arrives at the intersection (supposing that he keeps a constant speed).

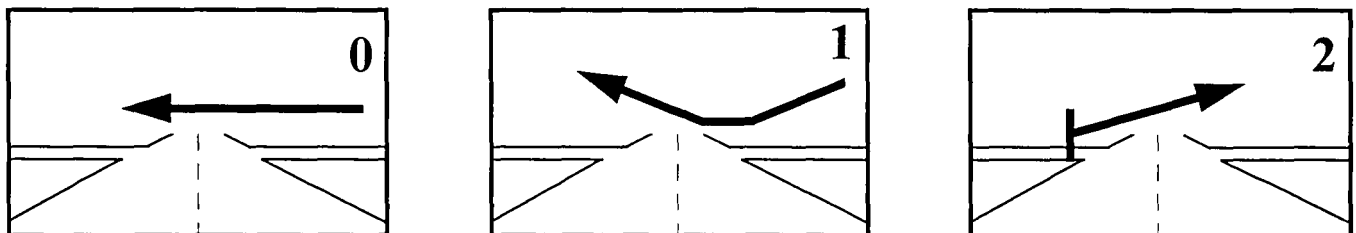


Figure 2. Pictograms of the 3 configurations.

**Conditioning Track** - Specific attention was paid to road design (geometry and visual aspect) to contribute to drivers' conditioning. A track of 17 km of French national trunk road was built on the basis of a representative study of the French network in terms of road geometry. In the studied intersection, road signs and telegraph posts enhanced the perception of distances. Drivers crossed different kind of vehicles (cars, trucks and buses) and met several intersections with other vehicles crossing.

**Driver population** - The experiment was carried out on 68 test-drivers of differing social status. The breakdown of the population in the different configurations according to age and sex (excluding 3 subjects because of simulator sickness or technical problems) is given in table 1.

**Table 1.**  
**Breakdown of Drivers in the 3 Configurations**

Driver Breakdown	24 Women		41 Men	
	Nb	Mean age	Nb	Mean age
Config. 0	8	34	14	34
Config. 1	8	34	13	35
Config. 2	8	35	14	37

**Experimental protocol** - During the experiment a psychologist was seated in the front passenger seat and asking general information. She could also check drivers' speed at the beginning of the test to help them control their speed. This help made up for the lack of speed feedback in a motionless driving simulator, the only speed indicators being the speedometer, the sound and the landscape motion. The psychologist stopped to intervene at several kilometers before the critical intersection. Drivers were told to drive for half an hour, respecting the highway code, therefore with a speed limit of 90 km/h. They were told that they had to drive on a first track for a training period and later on a second track for a driver behavior study. In fact there was only one track and the critical situation happened after about 15 minutes.

After the experimental session, drivers were interviewed by another psychologist. First they described their perceptions and interpretations of the situation. Secondly, they watched and commented on the video recorded during the session, in order to reposition their perceptions and interpretations. The interpretations were then translated by psychologists into safety diagnosis indicating the level of safety perceived by the drivers: "safety state", "risk state" and "danger state".

**Recordings** - The video recording enables to observe glance diversions and estimate the moment at which driver detected the adverse vehicle (figure 4), except for the last configuration in which the adverse vehicle remains in the middle of the drivers' field of view. In parallel to the psychological data and video recording, numerical data of the simulation were stored (list of variables in table 2). These data were post-processed (with numerical filtering of

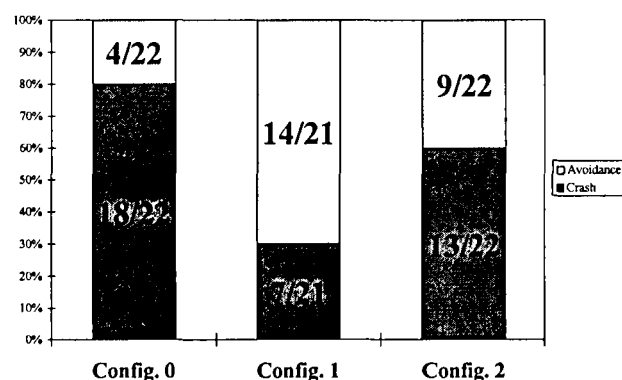
behavioral variables) and represented graphically in order to be correlated to the glance diversion and to the changes in safety diagnosis of drivers (figure 5).

**Table 2.**  
**List of Recorded Numerical Variables**

Dynamic variables	Behavioral variables	Adverse vehicle
Position Longitudinal speed Lateral speed Longitudinal accel. Lateral accel. Yaw angle Front wheel slipping Collision flag	Gas pedal travel Brake pedal travel Steering wheel angle	Position

## ANALYSIS OF DRIVERS' BEHAVIOR

**Principle of the Analysis** - The analysis carried out consists in comparing the behavior of drivers who avoided the crash with those who crashed. After the comparison of the initial conditions within and between the 3 configurations, the first perception of the adverse vehicle, interpretations, longitudinal and transversal actions of drivers are studied. All these comparisons are based on non-parametric statistic tests (Wilcoxon-Mann-Whitney test for sample comparison, and Kendall test for rank correlation). The avoidance rates are presented in figure 3. Because most drivers in configuration 0 crashed, the analysis in that case is focused on the reason why approximately half of driver's only perceived the adverse vehicle just before the crash.



**Figure 3.** Crash and avoidance rates according to the configuration.



Figure 4. Views of the video recording, with examples of glance diversion (configuration 1).

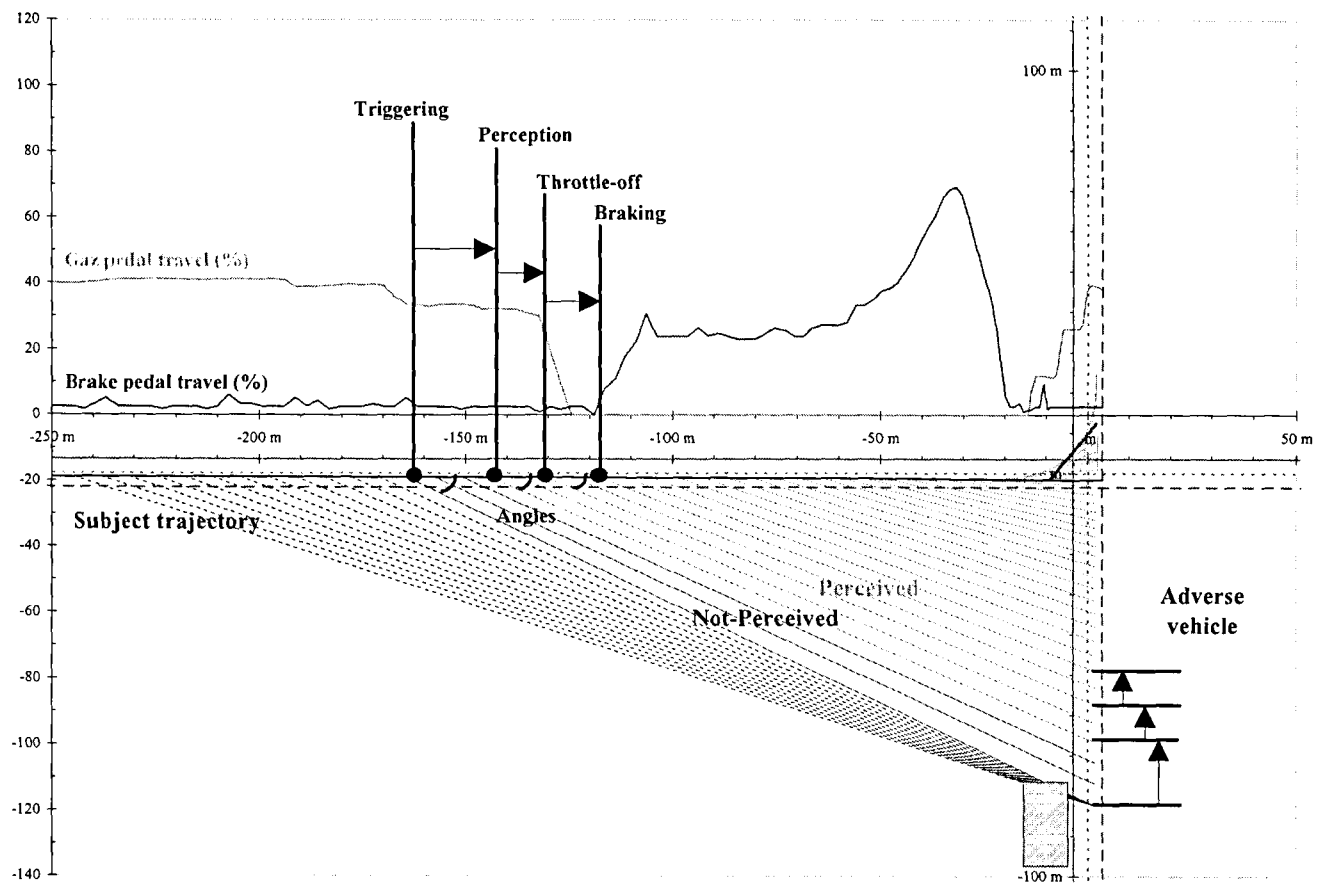


Figure 5. Graphical representation of part of the numerical recorded variables (configuration 1).

**Initial conditions** - At 500 m from the intersection, drivers' speeds are statistically comparable between the different configurations. In configuration 1, there is no statistical difference in speeds at 500 m, 250 m and at the triggering of the adverse vehicle between drivers who avoided and those who crashed. In configuration 2, in which the adverse vehicle is visible much before its starting, there is no statistical difference in speeds at 500 m, however speeds at 250 m and at the triggering of the adverse vehicle are significantly different (difference of 9 km/h of medians). Drivers' anticipation therefore plays a significant role in the success of the avoidance action. In configuration 0, drivers who perceived the adverse vehicle much before the collision were driving 15 km/h faster (median value) than those who did not (this difference is statistically significant). This can be explained by a lower angular position of the adverse vehicle at the moment of its triggering. The angle between the driver's heading and the adverse vehicle from the point of view of driver's eye is actually :

$$\alpha = \text{atan}\left(\frac{\text{waiting Distance to intersec. of adverse vehicle}}{\text{triggering Time to intersec.} \times \text{driver's Speed}}\right) \quad (1.)$$

The median of this angle is 34° for those who only perceived the adverse vehicle just before the collision, compared to 30° for the others (the distributions being statistically different). This suggests that drivers have more difficulties to detect the adverse vehicle for higher angular positions of this vehicle.

**First perception** - Drivers' first perception cannot be determined in configuration 2 because of the central position of the waiting vehicle making it impossible to observe glance diversions. In configuration 0, drivers who perceived the adverse vehicle just before the collision (at a median distance of 16 m from the intersection, compared to 114 m for other drivers), perceived it statistically for a similar angular position, around 30° to the right. This corroborates the previous findings concerning perception problems. In configuration 1, first perception occurred statistically in the same condition for drivers who avoided and those who crashed (the median of the adverse vehicle angular position being 25° to the right, compared to 27° at the triggering of this vehicle). Drivers perceive the adverse vehicle 0.9 s after its triggering (median value).

**Interpretation** - In configuration 0, 6 out of 8 drivers who perceived the adverse vehicle before their crash estimated themselves in a "safety state" as a first diagnosis. The 2 other drivers made a "risk state" diagnosis but did not decelerate. In configuration 1, 10 out of 12 drivers who avoided made a "risk state" first diagnosis. On the other hand, 5 out of 7 drivers who crashed made a "safety state" diagnosis. This distribution is statistically significant (Fisher exact test). In configuration 2, the speed, at the starting of the adverse vehicle, of drivers who made at least one "risk state" diagnosis is statistically lower than that of

those who remained in a "safety state". Among the 9 drivers who avoided, 6 were in a "risk state" at the starting of the adverse vehicle, compared to 3 among the 13 drivers who crashed. Therefore, interpretation and anticipation play a significant role in the avoidance of those accidents.

**Longitudinal reactive maneuvers** - Drivers' reactions following the first perception of the adverse vehicle on the gas and brake pedals and their effect on their speed is now studied. In configuration 0, drivers who perceived the adverse vehicle long before the crash reacted as late as the others (no statistical difference in the moment of throttle-off between the two groups) : 2.1 s after the perception and 0.7 s before the crash (median values). This must be due to their too optimistic safety diagnosis. For both groups, the speed reduction in the last 250 m is not significant (median lower than 5 km/h).

In configuration 1, the early perception of the adverse vehicle leaves at least 4 s for the drivers to react. Drivers who crashed throttled-off 1.7 s after the triggering of the adverse vehicle, compared to 1.1 s for those who avoided (median values). Either they did not brake at all or they braked late in the last 0.5 s before the crash. Those who avoided braked in a period of 3.5 s after the triggering of the adverse vehicle (the crash should occur 6.1 s after this triggering). The maximum brake pedal travel is statistically identical between the two groups. Foot displacement time (from gas to brake pedal) is statistically lower for drivers who crashed (median being 0.4 s compared to 1.1 s). Their maximum brake pedal speed is significantly higher. This can be explained by the fact that those drivers reacted consecutively to a "danger state" diagnosis. However, maximum brake pedal speed is not correlated to the speed variation. The median of minimum speed of those who avoided is 42 km/h compared to 87 km/h for those who crashed, representing a 56 km/h reduction from the speed at 250 m from the intersection, compared to 11 km/h for those who crashed. The way drivers brake seems therefore to have less influence than the time at which they begin braking.

In configuration 2, all throttles-off are followed by an immediate braking, these actions being all realized in a "danger state" diagnosis. Drivers who avoided start their throttle-off action 0.8 s after the starting of the adverse vehicle (median value). Those who crashed have a supplementary delay of 0.5 s which is statistically significant. There is no significant difference in the foot displacement time between those two groups (medians being respectively 0.4 and 0.3 s). Maximum brake pedal travel and maximum brake pedal speed are also statistically identical between the two groups. This is consistent with the fact that all drivers react in the same "danger state" diagnosis. Maximum brake pedal speed is not correlated with speed reduction. The median of minimum speed of those who avoided is 0 km/h compared to 44 km/h for

those who crashed, representing a 84 km/h reduction from the speed at 250 m from the intersection, compared to 55 km/h for those who crashed. The way drivers brake seems therefore to have less influence than the time at which they begin braking.

**Transversal reactive maneuvers** - Drivers' reactions on the steering wheel following the first perception of the adverse vehicle, and their effect on the lateral position of the vehicle is now studied. In configuration 0, all of the 14 drivers who applied a movement on the steering wheel tried to steer on the left, which is the direction of the adverse vehicle. The steering angle exceeds 25° in 8 cases.

In configuration 1, the maximum steering wheel angle is correlated with the minimum distance between the two vehicles, showing that more the situation is critical, more the drivers tend to steer. Among the 9 drivers who steered, only 5 reached at least a 25° angle. Final positions of the drivers are always located on the left of the lane (despite some right steering angles), and are less than 75 cm from the center position in the lane (except in 2 cases).

In configuration 2, 16 drivers applied a steering wheel movement, exceeding 25° in 14 cases. Steering wheel movements are homogeneously distributed on the right and on the left, with 5 cases in which final position exceeds 1 m away from the center position in the lane. This concerns 3

drivers who crashed and 2 drivers who would have avoided the crash by braking action only.

In those configurations, drivers' steering wheel movements are therefore either unadapted, inefficient or useless.

**Configuration specific results** - In configuration 0, collision rates are significantly higher than for configuration 1 (Fisher exact test). This is all the more significant as this configuration was less tricky (constant speed of the adverse vehicle and shorter time in driver's lane). This trend seems to be linked to the higher angular position of the adverse vehicle and could be explained by :

- the static position of the adverse vehicle in the peripheral vision field of drivers (due to its constant speed) which is less sensitive to fixed objects, making them more difficult to detect it,
- the hypothesis of a relevant cognitive field outside of which drivers do not take information into account, also explaining why drivers who detect the adverse vehicle early still have a statistically higher accident rate and more often make a "safety state" diagnosis than those of configuration 1,
- a simulator bias such as the position of the horizon line independent of drivers' eye position possibly causing the rearview mirror to mask the adverse vehicle.

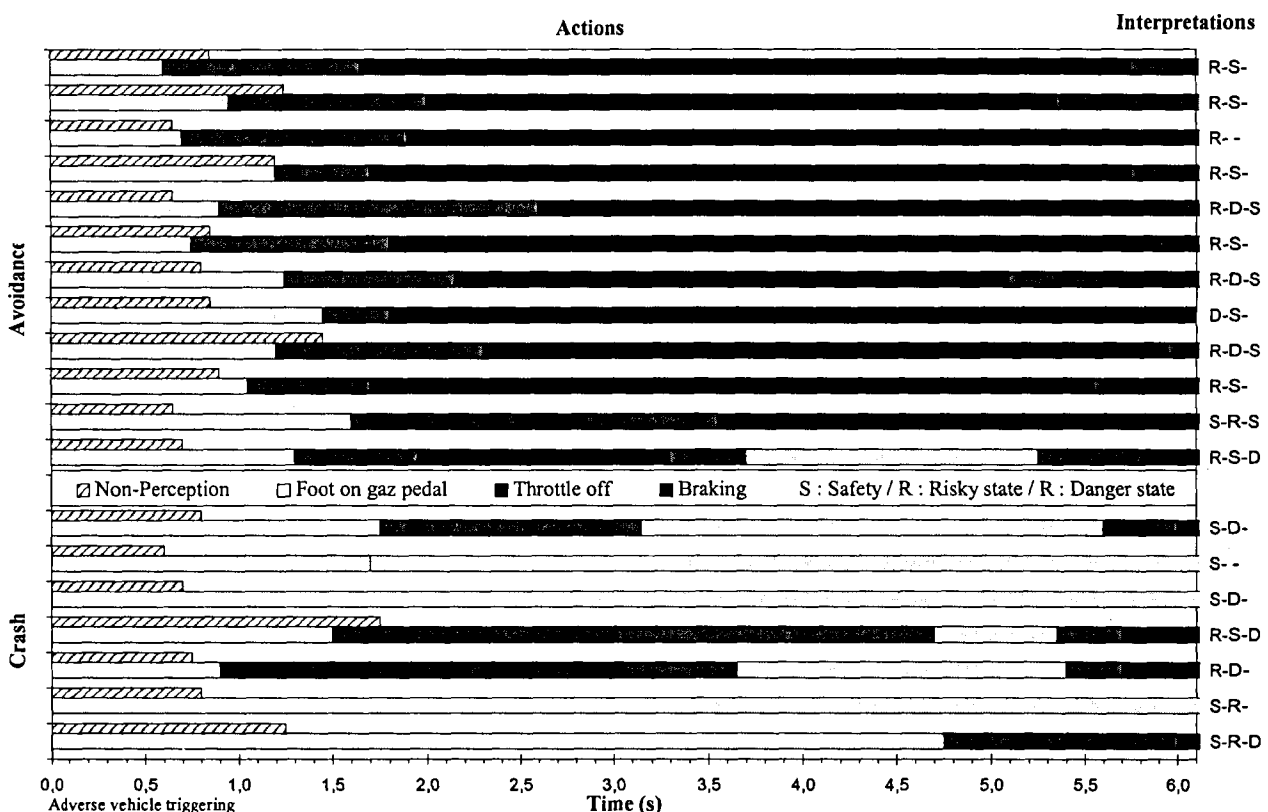


Figure 6. Time history of longitudinal actions in configuration 1.

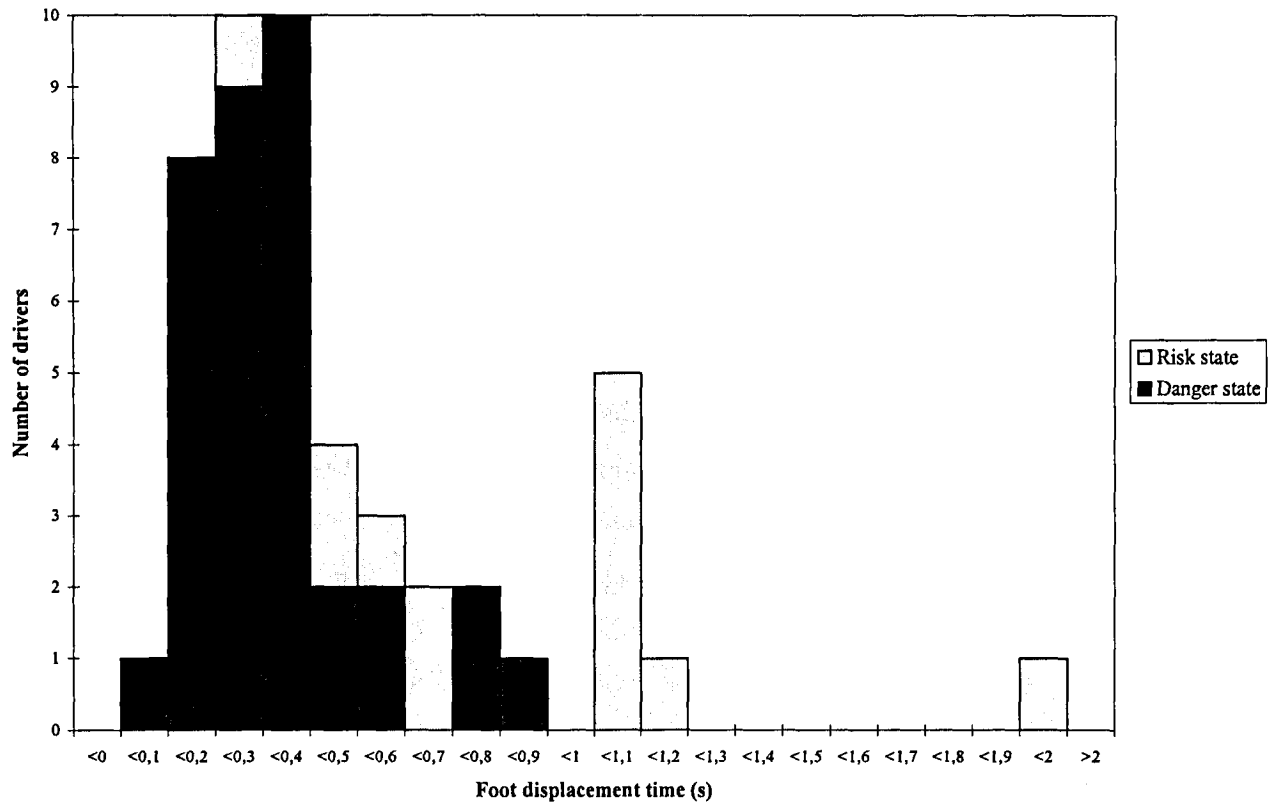


Figure 7. Breakdown of foot displacement time in the 3 configurations.

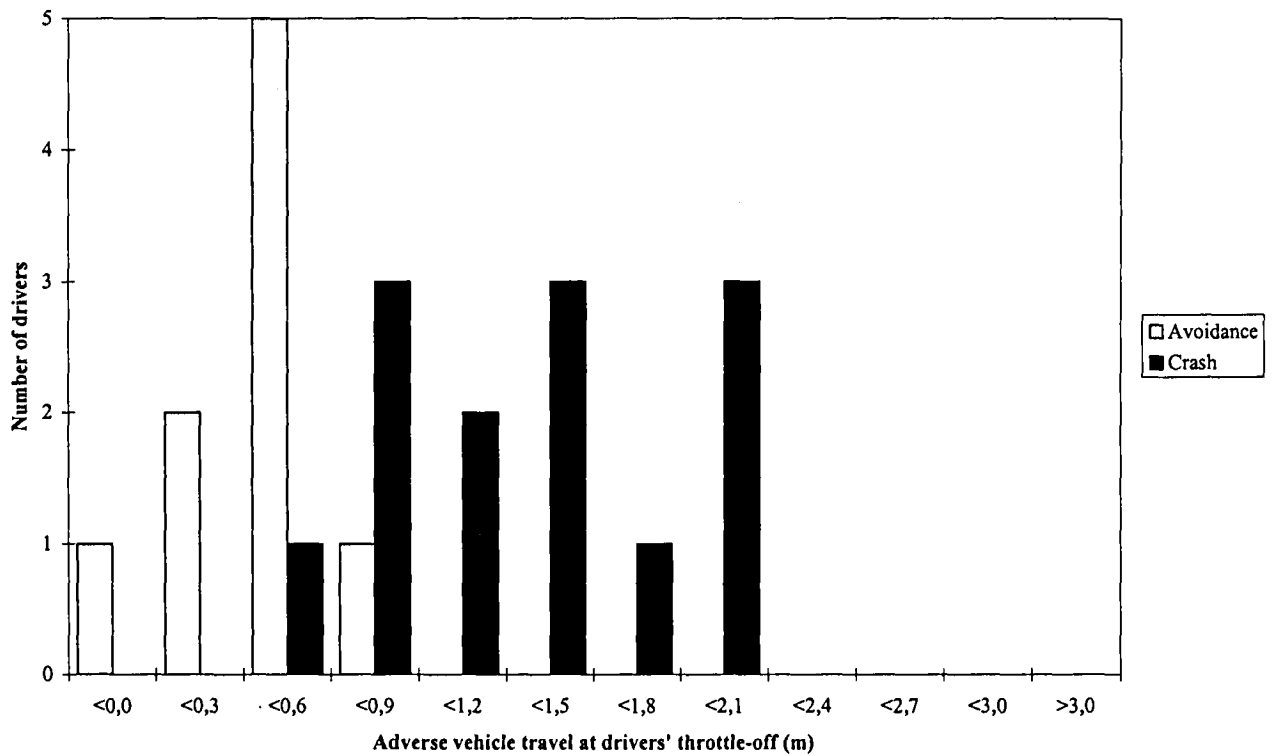


Figure 8. Breakdown of adverse vehicle travel at drivers' throttle-off in configuration 2.



In configuration 1, the behaviors of those who avoided and of those who crashed stand in sharp contrast (figure 6). Actually, drivers who avoided have highly anticipated the critical situation with precautionary braking actions before the situation becomes really critical, which is not the case for those who crashed.

In configuration 2, drivers who crashed are those who were driving faster and who throttled-off latest : speed at the starting of the adverse vehicle and throttle-off delay are significantly correlated. This can be explained by the double effect of over confidence as regards speed and attention.

**Overall results** - From the different configurations, the results highlight that :

- drivers had greater difficulty in detecting the adverse vehicle and diagnose the situation when its angular position is higher than 32° to the right,
- the first safety diagnosis was decisive in the avoidance of the crash,
- drivers who avoided are those who anticipated long in advance and decelerated before the situation became really critical,
- the way drivers braked seems to have less influence than the moment at which they braked,
- in those configurations, steering wheel movements of drivers were either unadapted, inefficient or useless.

This experiment also provides some useful data for kinematic accident reconstructions that are carried out for in-depth accident investigation. As an example, figure 7 provides the breakdown of foot displacement times for which throttle-off and braking occurred during the same safety diagnosis. Figure 8 gives the breakdown of the adverse vehicle travel at the beginning of drivers' throttle-off in configuration 2. An example of the use of such data is given by Tarrière (1996).

## DISCUSSION

**Validity of the experiment** - Compared to external observations of human behavior, experiments bring a certain bias due to the experimental context which may be slightly different from normal conditions and in which subjects may feel observed and modify their behavior. Simulator studies bring a supplementary bias due to :

- the realism of the simulation (through visual, auditory, force and movement restitution), which may affect drivers' perceptions and actions on vehicle controls,
- the virtuality of the context, which may modify drivers' cognitive interpretation of the situation.

Since drivers do not feel their deceleration when braking in a motionless simulator, they undoubtedly tend to overdose their actions. In this experiment, it is particularly the case for drivers who highly anticipate and proceed to a precautionary maneuver (partial braking). However it is

assumed that the lack of deceleration feedback for this action does not interfere with the time at which the driver initiated it. Moreover, in more critical situations, drivers' actions were quite extreme and reflex. It is thus assumed that they would not have been so different in a real situation. Interviews with psychologists have shown that most drivers felt as if they were involved in the situation, with some high stress reactions. Moreover, drivers' reactions are generally consistent with their interpretation. This tends to show that in a short and highly demanding task drivers tend to forget that they are in a totally safe driving simulator. From a more general point of view, drivers' speed at 500 m from the intersection has been found representative of real speeds on French national roads, highlighting also the simulator's relevance for long-duration tasks.

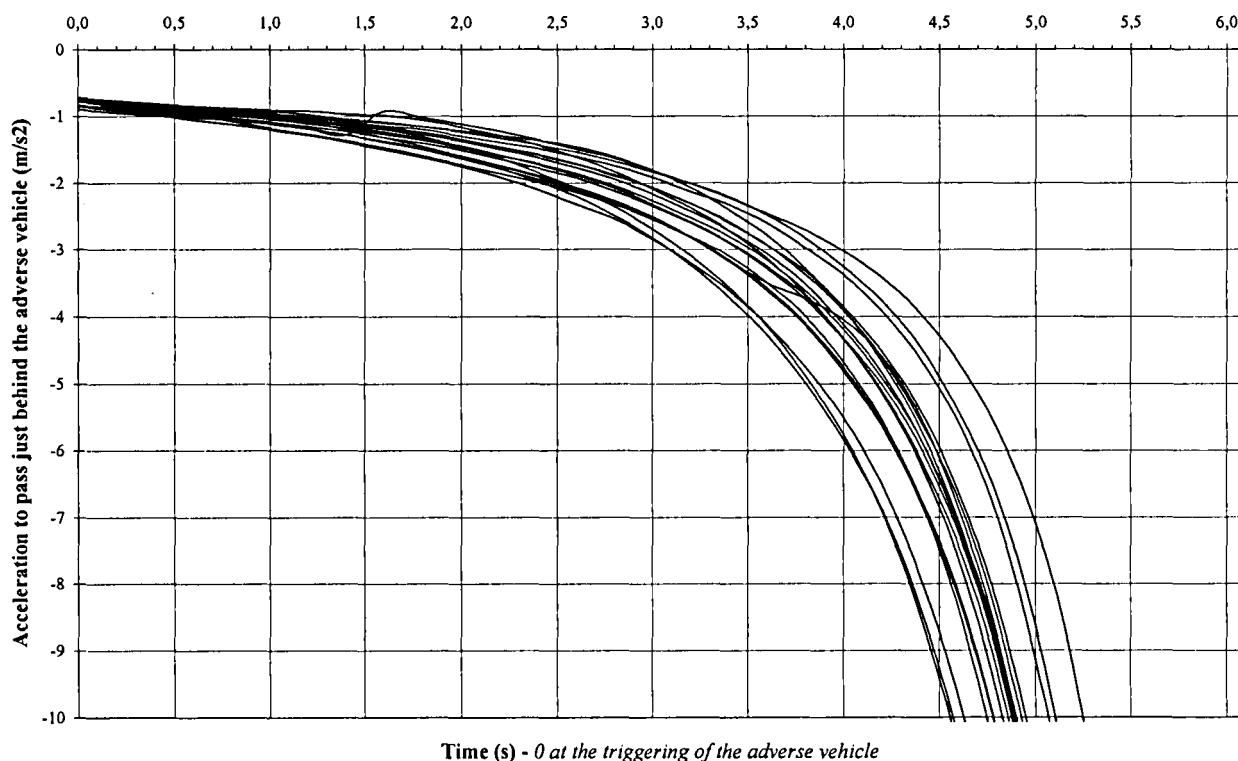
A better way to estimate the validity of the experiment, is to compare it to other similar experiments conducted on a real scale on test tracks. For obvious safety reasons, such experiments are not very numerous. Olson (1986) measured drivers' perception-response times, from the moment an obstacle hidden by a crest becomes visible to the moment the driver applies the brakes. The median of perception-response times in his experiment was 1.1 s, with a 0.4 s foot displacement time (median value). These results are very similar to those of configuration 2, with a 1.3 s braking time and a 0.3 s foot displacement time (median values). The slightly longer braking time may be explained by the fact that in configuration 2 the danger is not immediate : it takes a longer time for drivers to detect the movement of the adverse vehicle and interpret that it is going to cross their lane. Since the experiment presented in this paper was carried out on a motionless simulator, other similar studies conducted on a dynamic driving simulator also provide data to assess the validity of the experiment. The one conducted by Lechner (1991) is similar to configuration 2, with an adverse vehicle arriving at an intersection from the drivers' right, failing to yield and stopping in the middle of the drivers' lane. The authors found a mean foot displacement time of 0.2 s, similar to results of configuration 2. In their experiment, the mean braking time was 1.0 s but was found to be positively correlated with the time to intersection at the triggering of the adverse vehicle (2 s, 2.4 s or 2.8 s in their experiment), which explains why it is longer in configuration 2 (triggering time being 3.25 s in this configuration). The authors also noticed no difference in the realization of braking between those who avoided and those who crashed.

**Application to the specification of crash avoidance systems** - Even if braking action is not always the most efficient way to avoid a crash, it is the easiest to assist with intelligent systems and the most relevant to dissipate energy. It is therefore proposed to analyze the point to which braking may still be effective in avoiding the crash in each configuration. Knowing the kinematics of the adverse vehicle, it is possible at any time to compute the constant deceleration that the driver should apply from this moment to avoid the adverse vehicle with a given safety margin. Figures 9 and 10 provide, for each driver, the time-history of the deceleration that the driver should apply to pass 2 m behind the adverse vehicle, respectively in configurations 0 and 1. Figure 11 gives the deceleration that drivers of configuration 2 should apply to stop 2 m before the adverse vehicle's lane.

These graphics must be related to the moment at which the situation becomes objectively critical, which is not explicit in configurations 0 and 1. In these configurations, it is proposed to characterize this moment with the deceleration that the adverse vehicle should apply from this moment to stop at the intersection (this deceleration is here supposed constant, and it is proposed to call it "degree of

criticity"). It is assumed that, when this deceleration reaches a certain limit, the probability that the adverse driver actually applies the brakes to obtain this level of deceleration becomes relatively low. The risk that this driver will fail to yield becomes therefore high enough so that the right-of-way driver should take the decision to brake. It is here proposed to fix the limit for the degree of criticality at  $4 \text{ m/s}^2$ . This value is reached 2.3 s before the collision in configuration 0, and 1.5 s before the collision in configuration 1.

In configuration 0, perception and interpretation problems were identified. It therefore seems that a system aimed at helping drivers to detect the danger would be relevant. This requires detection of the adverse vehicle and estimation of its speed between 43 and 68 m from the intersection, when the adverse vehicle is at 35 m from the stop line, between  $26^\circ$  and  $37^\circ$  to the right. Figure 9 points out that it is still possible to avoid all crashes if the right-of-way vehicle brakes 2 s before the collision at  $6.5 \text{ m/s}^2$ . This leaves too short a time for the driver to react to an alarm and therefore would require an automatic braking system.



**Figure 9.** Deceleration curves of drivers to pass 2 m behind the adverse vehicle in configuration 0.

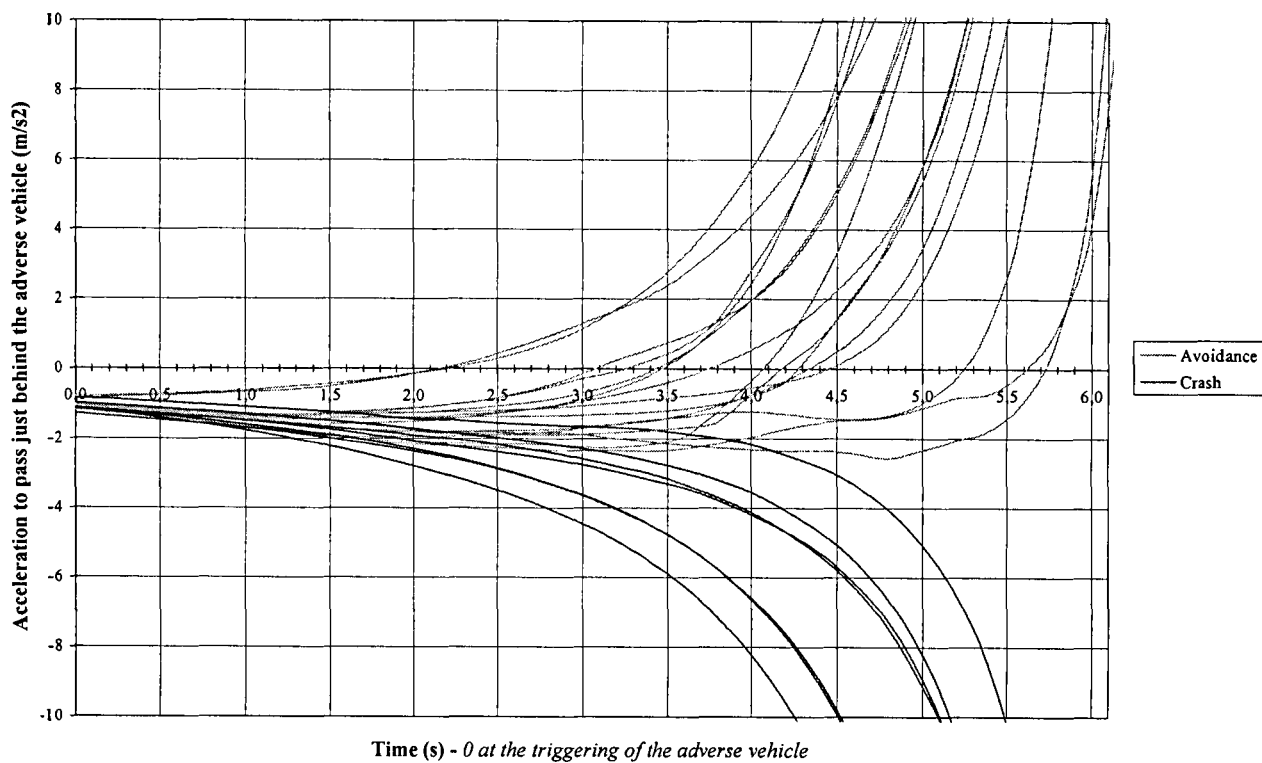


Figure 10. Deceleration curves of drivers to pass 2 m behind the adverse vehicle in configuration 1.

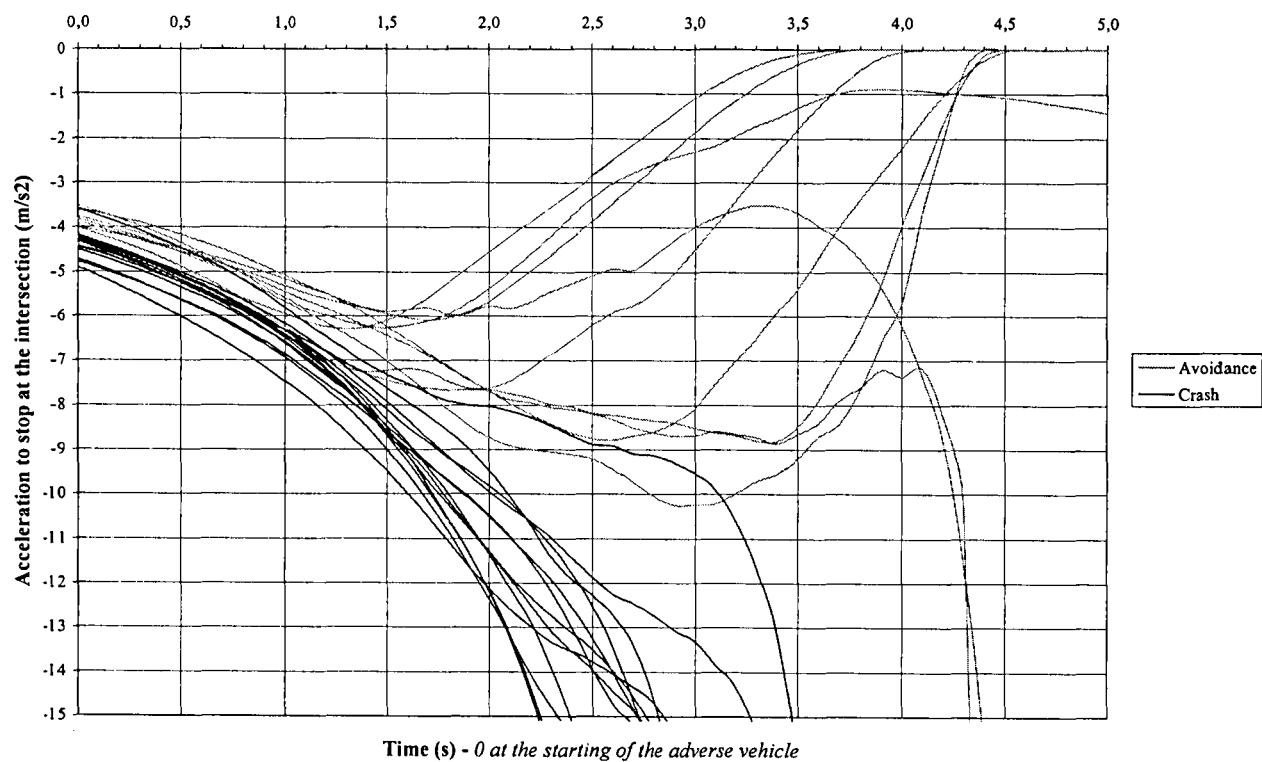


Figure 11. Deceleration curves of drivers to stop 2 m before the adverse vehicle's lane in configuration 2.

In configuration 1, the problem essentially stems from the interpretation of the adverse vehicle kinematics. The crash being foreseeable only 1.5 s before the collision, the system should also apply the brakes automatically. It should detect the adverse vehicle and estimate its speed between 27 and 51 m from the intersection, when the adverse vehicle is at 10 m from the stop line, between 13° and 21° to the right. Figure 10 shows that braking at  $6.5 \text{ m/s}^2$  would only prevent 4 crashes out of 7. The speed reduction in the remaining crashes would however be significant (at least 35 km/h) and could moreover be accompanied by an anticipatory deployment of passive safety systems.

In configuration 2, most drivers rapidly recognize the danger on themselves. To improve their reactions, an intelligent crash avoidance system should therefore also apply automatic braking. To be acceptable, such a system should brake before all drivers, which means 0.9 s after the starting of the adverse vehicle (having then traveled 0.5 m, and being at 5 km/h). Braking at  $7 \text{ m/s}^2$  would then avoid all collisions.

However such automatic braking systems are today in the research phase and are facing reliability problems. In configuration 2 for instance, it is not obvious to distinguish early between a non-right-of-way vehicle that is actually crossing the intersection, and another one that is safely turning right. Moreover there are other complex intersection infrastructures in which vehicle kinematics could make the system erroneously believe it is in a danger situation. It is clear that any inopportune activation of such systems would have negative consequences on the acceptability of the system, but also and especially on safety. The technological limits for automatic braking triggering could be pushed back thanks to the addition of criteria based on the driver behavior. Actually, emergency braking dynamic assistance (active braking booster) follows this direction to the extreme, with no data taken on the external situation (environmental source of danger), the trigger being only dependent on the driver's actions. The experiment presented here also provides data for the specification of such systems.

This experiment provides data quantifying throttle-off and braking actions combined with psychological data on drivers' diagnosis of the situation. It is therefore possible to determine optimized triggering criteria that maximize triggering in "danger state" and minimize triggering in "risk state". In this study, 3 different kinds of criteria relative to actions on the gas pedal were taken into account. Those criteria were then also combined with another characterizing the throttle-off. Each studied criterion was based on up to 4 distinct parameters. The optimization provided the best numerical conditions for each kind of criterion. A numerical simulation of the effect of an active braking booster based on these criteria was then carried out

in order to compute the avoidance rate and the decrease in collision speed generated by the system. This assumes that drivers would not have modified their braking force. The analysis gave significant results. However, no criterion was found to reject all inopportune triggering.

It is clear that for the specification and efficiency assessment of active safety systems this experiment is not representative enough to draw any conclusions, due to the number of drivers and situations tested. Actually, inopportune triggering must be studied in many other various non-critical driving situations of daily driving. Moreover, on a motionless simulator drivers probably tend to overdose the corresponding braking actions, which requires further experiments on test tracks or open roads.

## CONCLUSION

The experiment presented here points out the benefit of a motionless driving simulator for the analysis of driver behavior in certain driving situations. It is assumed that such experiments are suited to the analysis of maneuverability\* accidents (in which the driver is put in a dangerous situation by external conditions) and guidance\* accidents (in which the critical task is to guide the vehicle among different obstacles). It seems that control\* accidents (due to a loss of control of the vehicle) are less suited to experiments on a motionless simulator and that pilotability\* accidents (due to a driver error) should be studied through observations (in-depth accident investigations for instance). This kind of experiment also seems complementary to in-depth accident investigations since it requires data on the actual kinematics of vehicles in real world accidents, but also gives data for accident reconstructions. This kind of experiment provides useful data for the specification and efficiency assessment of crash avoidance systems. Concerning the different configurations tested, it has been pointed out that :

- drivers have more difficulties to detect the adverse vehicle and diagnose the situation for higher angular positions of this vehicle,
- the first safety diagnosis is decisive in the avoidance of the crash,
- drivers who avoid are those who anticipate far in advance and decelerate before the situation becomes really critical,
- the way drivers brake seems to have less influence than the moment at which they brake,
- in these configurations, steering wheel movements of drivers are either unadapted, inefficient or useless.

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\* A definition of these terms is given by Perron 1996.

## ACKNOWLEDGMENTS

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# APPLICATION OF INTELLIGENT TRANSPORTATION SYSTEMS TO ENHANCE VEHICLE SAFETY FOR ELDERLY AND LESS ABLE TRAVELLERS

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## ABSTRACT

Elderly drivers have a high accident rate per kilometer driven, though not per person per year, and elderly pedestrians and transit users also have above average accident rates. The potential of Intelligent Transportation Systems (ITS) to enhance vehicle safety for elderly and less able travellers is examined. For car drivers, Advanced Vehicle Control and Safety Systems (AVCSS) and Advanced Transportation Information Systems (ATIS) should make driving easier, less stressful and safer. Transit users should be helped by better information before and during travel and by smart cards. Pedestrians with visual impairments can be helped by hand-held guidance equipment and by talking signposts; road-crossing facilities can be improved to benefit everybody.

## INTRODUCTION

Intelligent Transportation Systems (ITS) is the term used to describe the application to road transportation of advanced technologies including computing, sensors, communications, and controls. These technologies have been in use for some time, but the rate of application has increased dramatically in the past few years. Real-time display of information in public transportation systems is becoming common, multimodal information terminals are starting to appear, major rental car companies have been offering in-vehicle navigation systems since mid-1996 and automobile manufacturers now offer these systems as options. These systems are intended to improve the safety, efficiency and capacity of the highway system.

Almost all developed countries have growing elderly populations and a large increase in the number of elderly and less able drivers. In Canada, the population of people aged 65 and over is expected to increase from 3.2 million in 1995 to 7.8 million in 2025; already, about 10 percent of the adult population of Canada have specific

transport disabilities (Mitchell, 1997). In the U.S., the population aged 65+ is forecast to more than double between 1990 and 2030 (NHTSA, 1996).

The number of licensed elderly drivers has increased rapidly, and is likely to continue to do so. In the U.S. in 1994, 90 percent of men and 58 percent of women aged 70 years and over held driving licences. Even for people over 85 years of age, 75 percent of men and 26 percent of women held licences. As early as the year 2020, elderly and less able drivers and travellers will probably contribute more than 20 percent of the total market for ITS equipment. Their requirements should not be neglected in ITS developments, on commercial as well as safety grounds.

As people age, they become more fragile and therefore more vulnerable to accidents. Elderly people have higher than average accident rates as pedestrians, as transit users and, per kilometer, as drivers (NHTSA, 1996; TRB, 1988; Department of Transport, 1991). A given accident causes more damage to an elderly individual, and older people take longer to recover from injury (Evans, 1991). Injuries are more likely to be fatal for people over the age of 65. Many elderly people are more concerned about safety and security than are younger people.

The purpose of this paper is to examine the potential of two classes of ITS system, Advanced Vehicle Control and Safety Systems (AVCSS) and Advanced Traveller Information Systems (ATIS) to help elderly and less able drivers and travellers. The paper lists the safety and security concerns of elderly and less able people and reviews the potential of ITS to improve the safety of elderly and less able drivers, transit passengers and pedestrians.

The important role of ITS in trip planning for all modes is not covered in this paper.

## WAYS IN WHICH ITS CAN IMPROVE SAFETY

The ways in which ITS can improve transport safety vary between the different modes. Their main contributions are towards primary safety - that is, preventing accidents from happening. In the case of car travellers, it may also be possible to improve secondary safety - that is, reducing injuries to people when an accident does happen.

Furthermore, widespread implementation of these systems, taking care to maximize their potential for improving accessibility of public transit, will encourage elderly drivers to use other means of transport when age-related sensory, cognitive or motor deficits preclude them from driving safely, even with ITS enhancements. Using ITS to reduce the mobility cost of the decision to stop driving will increase road safety for all.

### Travel by Car

ATIS can provide information on traffic conditions, provide specialized weather forecasts and guide the driver to a selected destination. This information can warn drivers of congestion and severe weather, both conditions which elderly drivers try to avoid and that increase the risk of accidents. Navigation systems, which provide route guidance information, give drivers advance warning of junctions and lane changes. This reduces the pressure to initiate manoeuvres late, with consequent risk of conflict with other vehicles or sudden manoeuvres with the possibility of loss of control. This is discussed further in the section on ITS and car drivers.

AVCSS can provide information specifically to avoid collisions, improve visibility at night, assist with the longitudinal and lateral control of the vehicle and assist with speed control. Furthermore, occupant restraint systems will likely be able to adapt themselves to the occupant's size, weight, age and sitting position, to minimize injury in any particular collision.

### Public Transport Users

Although the main value of ITS to public transport users will be through better information before and during a journey, and the use of smart cards to pay fares, all of which will reduce stress and increase security for travellers, these systems will also directly improve safety.

Many injuries to bus passengers result from falls when boarding or alighting from the vehicle, or in the vehicle during a journey. They mainly happen when elderly passengers must stand while the bus is in motion, or hurry to board, pay the fare and find a seat. On-board displays that name the next stop, and stop request buttons that can be reached by seated passengers, will allow

passengers to remain seated until the bus has stopped. Elderly passengers are often concerned about the time it takes them to board and pay their fare. Using a smart card for fare payment reduces the things a passenger has to do while boarding. Non-contact smart cards do not need to be taken out before use - if a wallet or purse is placed on the card reader, the payment is made. Both of these technologies should reduce the numbers of falls while boarding and alighting from the vehicle. This is discussed in the section on ITS and public transport users.

### Pedestrians

Apart from improvements to light-controlled crossings, discussed in the section on ITS and pedestrians, the main safety benefit of ITS to less able pedestrians is the help it can give to prevent people walking into traffic areas and falling off railway platforms. For people whose vision is seriously impaired, who have a high accident rate as pedestrians, these areas pose very real dangers (Gallon et al., 1995).

## ITS AND CAR DRIVERS

In most countries the risk of accident involvement per driver per year decreases steadily with increasing age. In British Columbia in 1994, only 2.2 percent of drivers over 65 were involved in collisions, compared with 4.4 percent of all drivers. However, because elderly drivers drive less as they age, their accident rate per kilometer increases after the age of about 60, and sharply after the age of about 70-75.

Older drivers have more accidents than average at junctions, particularly at unsignalized junctions on two-lane roads, and are more likely to be involved in right of way violations. They have fewer single-vehicle accidents, accidents at night, accidents involving speeding and drink/drive violations. Older drivers are more likely to be "at fault" for accidents than middle-aged drivers, but only after the age of 75 are they more likely to be at fault than teenage drivers. Older drivers recognize that they have problems with night vision, turns across traffic and merging into lanes of traffic, along with failing to respond to road signs and signals (Malfetti et al., 1987).

The effects of aging are well known, though the abilities of older drivers vary greatly between individuals (TRB, 1988). Older people's vision usually deteriorates, particularly at night. This reduces the ability of older people to read signs and to see objects such as pedestrians in poor light. Their sensitivity to visual motion decreases, increasing detection failures and making traffic gap judgements less accurate. Their reaction time increases, particularly in complex situations (Stamatiadis et al., 1990) or when information location is uncertain (Ranney

et al., 1992). They become less able to divide attention between two or more tasks. This age-related decrease is characteristic of a switch from automatic, parallel processing to effortful, serial processing (McDowd et al., 1991). If ITS equipment is to help older drivers to continue driving safely, it must compensate for these effects.

Barkow et al. (1993) found that the primary concern of elderly and less able drivers was for greater safety. Of the ITS features wanted, the most favoured were driver's aids - cruise control, steering assistance, snooze alarm and a Mayday system to obtain medical or mechanical assistance. Second was information on roads, traffic and weather. Third were features that enhanced the ease and comfort of driving - an electronic memory to reset seats, steering and mirrors, and monitoring of vehicle condition (to minimize the risk of a breakdown or flat tire).

Drivers over 55 years of age report more problems than do those aged 35-44 with reading traffic signs, seeing clearly at night, turning their heads while reversing and when merging into high-speed traffic (Rothe, 1990). Drivers in Illinois over 65 years of age found that driving at night, in heavy traffic and at high speed on freeways had become more difficult (Benekohal et al., 1994a). Older drivers avoid bad weather and ice, night driving,

rush-hour traffic and limited access highways (Rothe, 1990; Benekohal et al., 1994b; Laux et al., 1990). Older people drive less frequently, and a smaller percentage of their trips include unfamiliar neighborhoods or major thoroughfares. Table 1 shows how ITS equipment has the potential to compensate for the effects of age-related impairment in drivers.

Some ITS equipment has the potential to increase the mobility of elderly and less able drivers by making driving easier. Other systems have the potential to improve safety by increasing the distance from which obstructions can be seen in darkness, by warning of obstacles in blind spots, by warning of conflicting traffic, by monitoring the condition of the driver and generally by helping with the aspects of driving that elderly drivers find difficult. Systems such as emergency alert (Mayday) can increase the security of drivers by enabling them to summon help if it is required. These systems were designed for all drivers, but they have the potential to provide particular benefits for elderly and less able drivers. The European DRIVE II Project EDDIT evaluated ITS equipment being used by elderly drivers (Oxley et al., 1995). The reactions of users were very positive and only one system caused distraction from the task of driving.

**TABLE 1.**  
**Car Driver Impairments, Safety Problems and ITS Equipment**

Impairment	Problems	ITS equipment
Increased reaction time. Difficulty dividing attention between tasks	Difficulty driving in unfamiliar or congested areas	Navigation/ route guidance Traffic information, VMS
Deteriorating vision, particularly at night	Difficulty seeing pedestrians and other objects at night, reading signs	Night vision enhancement In-vehicle signs
Difficulty judging speed and distance	Failure to perceive conflicting vehicles. Accidents at junctions	Collision warning. Automated lane changing
Difficulty perceiving and analyzing situations	Failure to comply with yield signs, traffic signals and rail crossings. Slow to appreciate hazards	In-vehicle signs and warnings. Intelligent cruise control
Difficulty turning head, reduced peripheral vision	Failure to notice obstacles while manoeuvring. Merging and lane changes	Blind spot/obstacle detection. Automated lane changing and merging
More prone to fatigue	Get tired on long journeys	Intelligent cruise control Automated lane following
Some impairments vary in severity from day to day. Tiredness	Concern over fitness to drive	Driver condition monitoring

(Source: Mitchell and Suen, 1997)



## Specific ITS Systems for Car Drivers

**Congestion and Weather Warnings** Traffic and weather information can be broadcast to vehicles for display as text messages or information on maps. These systems are already in service and enable drivers to take informed decisions not to drive in conditions they would find difficult or dangerous.

**Route Guidance** Navigation systems are in service that guide a driver to a selected destination, giving advance warning of junctions and necessary manoeuvres such as lane changes. During the EDDIT Project (Oxley et al., 1995), one driver described a navigation system as "a co-driver who knows the way". Vocal instructions along with turn-by-turn visual guidance reduce memory load and visual interference with the primary driving task, and offer the most dramatic improvement and error reduction of older drivers' performance. These systems certainly reduce driving stress and, by avoiding the need to make lane changes or turns shortly before a junction, should reduce conflicts and accidents.

**Obstacle Detection** Systems already exist to detect obstacles behind and beside a vehicle during low-speed manoeuvres such as parking. Prototypes of similar systems can warn of vehicles in blind spots or converging during merges and lane changes. These can warn the driver and prevent conflicts and collisions.

**Night Vision Enhancement** Several systems are being developed to improve vision for drivers at night. Some illuminate the roadway to the front of the vehicle with radiation outside the visible spectrum (i.e., ultra-violet or infra-red radiation) and use fluorescence to enhance visibility directly, or process the radiation reflected back to a sensor array to generate images of objects that would not be visible to the driver's naked eye. Other systems generate images from thermal energy emitters (particularly living beings) in the environment. The detection range for pedestrians, obstructions and curves in the road can be increased considerably. Some of these systems are based on night-vision technology already in military service. Some allow the driver to see objects directly through the windshield, and others project a processed image onto a head-up display (HUD) inside the windshield, through which the outside world can still be seen (conformal imaging). However, older drivers may be particularly vulnerable to cognitive capture, a phenomenon whereby a HUD preempts visual attention and prevents detection of critical outside objects (Tufano, 1997).

**Intelligent Cruise Control and Lane Keeping Assistance** Intelligent cruise control (ICC) is a system for controlling a vehicle's speed and distance behind a preceding vehicle. Versions that will soon be

commercially available control the vehicle's speed to a pre-set value while maintaining a safe headway between vehicles. Future variants will tell the driver if the pre-set speed exceeds the local limit, and ask if the driver wishes to comply. They may take control of accelerator and brake to prevent rear-end collisions, if a dangerous situation is detected. Further into the future, ICC systems may automatically limit the vehicle speed to the local limit and reduce speed when approaching a bend, a yield sign or red traffic signal. Local speed limits could be varied by time of day or weather condition.

Prototype systems exist to provide assistance with lane keeping. These apply small forces to the steering to 'nudge' the vehicle into the centre of the lane it is following. They only work when the driver is holding the steering wheel, and the forces can be over-ridden by the driver if necessary.

ICC and lane-keeping assistance are particularly likely to benefit older drivers, who may neglect the low-level sub-tasks involved in course maintenance while performing higher-level subtasks such as visual search or route planning. ICC and steering assistance will preserve course maintenance when necessary to compensate for difficulties in dividing attention during high cognitive task loads.

**Collision Warning and Avoidance** Intelligent cruise control can provide protection against rear-end collisions. Obstacle detection systems to warn of conflicts while merging or changing lanes, which elderly drivers find difficult, are likely to be available within a few years. Elderly drivers are more likely than average to be involved in collisions when turning across traffic or at uncontrolled junctions. Trials with a gap-measuring system to help drivers turn across traffic have given promising results (Oxley et al., 1995), but any such system is many years from commercial implementation. Systems to warn of dangerous situations in the more complex case of general manoeuvres at uncontrolled junctions are likely to be many years in the future.

Furthermore, the effectiveness of a collision warning depends critically on whether the driver is processing available information in serial or in parallel (Najm et al., 1995). The implication here is that if the technical difficulties can eventually be solved, older drivers may be better served by an automatic control intervention in the event of an imminent collision, because a collision warning may interfere with the driver's primary task of vehicle control. However, such a system may not be well accepted by drivers, although older drivers have indicated a wish for steering assistance.

**Driver Condition Monitoring** Development is well advanced for systems that monitor the condition of the driver and warn of impairment by fatigue, alcohol or a

variable disability. These are likely to appear first on commercial vehicles, but could well be applied to cars in due course.

**In-vehicle Signing** Systems will be developed eventually that display road signs inside the vehicle and warn drivers of hazards or unusual conditions ahead. These will need extensive monitoring of road conditions and many transmitters to relay information from the road to the car. The investment in this infrastructure is likely to delay the implementation of these systems. Alternatively, details of road signs could be stored with the digital map for the navigation system, for display at the appropriate time. In this case the problem is keeping the data base updated. An autonomous system could not display temporary signs such as "Diversion", "Road works" or "Flood".

**Smart Occupant Protection Systems** Occupant protection systems such as seat belts and air bags are designed to protect a large male occupant in the most severe survivable accident. Because of this, they may apply greater forces than are necessary to people who are small, light and sit near to the steering wheel. In particular, they may cause injuries to a fragile older person in a relatively minor accident that could have produced no injuries if the restraint systems had been tailored to the attributes of the specific occupant. It is possible to imagine an occupant protection system that uses sensors to measure occupant weight and sitting position, and a smart card to define occupant age, gender and other characteristics (as well as automatically positioning seat, mirrors and steering wheel to suit the individual). In a given crash, the system would then adjust the loads applied to the occupant to be the lowest necessary to restrain them. Restraint systems are already in service that pre-tension and lock seat belts to minimize the movement of an occupant during a crash. Smart restraint systems would extend development further.

## ITS AND PUBLIC TRANSPORT USERS

For older people no longer able to drive safely even with the benefits of ITS, the increase in safety, convenience and ease of use that ITS affords elderly and less able users of public transit will encourage the decision to stop driving. Furthermore, travel by public transport vehicles is much safer than travel by car or on foot (Department of Transport, 1991). Problems with using buses currently include walking to the stop, waiting at the stop, climbing the steps at the entrance to the bus, pressure of time when boarding, paying the fare and finding a seat. There are also information problems: not recognizing the bus service required, difficulty recognizing the destination stop and not knowing the fare required. Overall, the need to move quickly while using public transport vehicles reduces in-vehicle safety, causing stress for elderly and less able passengers, and increasing the danger of accidental falls. In Britain, in 1976, 14 percent of casualties to bus passengers occurred in collisions, 29 percent during emergency action and 57 percent as a result of falls and other incidents during normal operations. Of the casualties not involving collisions, 43 percent were aged over 60 years. More recent statistics show that 50 percent of those passengers killed or seriously injured on buses are people aged over 60, despite only 27 percent of all passengers being of this age (Department of Transport, 1991).

ITS technologies are being used to improve the efficiency, productivity, reliability and in-vehicle safety of bus services. These include Advanced Traffic Management Systems (ATMS), Automatic Vehicle Location (AVL), Automatic Vehicle Identification (AVI) and communication between buses and a control centre (Schweiger et al., 1994). ITS technologies can help all passengers, by providing information or in other ways, and in many cases will be particularly helpful for elderly and less able passengers (see Table 2).

**TABLE 2.**  
**Bus Passenger Impairments, Problems and ITS Equipment**

Impairment	Problems	ITS equipment
Cannot stand for long, sensitive to cold	Unable to stand while waiting at bus stops	Display of waiting time at home, at bus stop on hand-held unit
Poor vision	Cannot read service number	Service display at bus stop Audio announcement by bus
Poor vision	Cannot see community bus in time to hail it	Hand-held device for communication between bus and passenger

Lack of manual dexterity, cannot do things quickly	Paying cash fare while boarding. Risk of falling while hurrying	Smart payment card
Poor vision, unfamiliar with area	Cannot identify destination stop	Display name of next stop in bus
Impaired hearing	Hearing announcements	Induction loop in bus
No vision	Finding bus stop, knowing which stop for which bus route	Talking signs, stops that announce route name or number

Smart payment cards can reduce the number of actions a passenger has to complete in a limited time while boarding a bus. Displaying the name of the next stop inside the bus gives passengers confidence and provides extra time to alight. In the medium future it should be possible to receive and display real-time transit information on a hand-held unit. This should reduce waiting times at bus stops and increase the perceived safety and security of passengers by providing information on the operation of the service.

ITS equipment can be used to improve security. With AVL and a communication system the driver can summon assistance quickly in response to any incident. Safety can be improved by systems to detect passengers close to the bus where the driver cannot see them, as is being tested on school buses in the U.S. There may be scope for people detectors to warn the driver if a passenger is trapped in the doors.

## ITS AND PEDESTRIANS

Older persons have the highest per capita pedestrian fatality rate of any age group (NHTSA, 1996). In Britain in 1989, nearly half of all pedestrians killed on the roads were over 60, although people over 60 formed only 20 percent of the total population (Department of Transport, 1991); in Canada in 1992, 32 percent of all pedestrians killed in traffic accidents were aged 65 or more, while 12 percent of the population were over 65. Various surveys show that about 30-35 percent of elderly and less able

pedestrians found traffic or crossing roads a significant difficulty (Hitchcock et al., 1984). In the U.S., two-thirds of older people in two U.S. metropolitan areas feared for safety while walking (Knoblauch et al., 1995). They were afraid of being attacked, being hit by a car or falling.

In Britain, a survey found that virtually all visually impaired independent travellers reported at least one accident, and over half had sustained injuries (Gallon et al., 1995). Visually impaired people have a higher frequency of walking accidents than sighted people and are more likely to be injured. Visually impaired people also have more accidents than sighted people when crossing roads, and over a third of respondents had experienced accidents involving steps. Of the respondents who travelled by rail, 35 percent had experienced at least one accident. Twenty-three percent had had an accident during boarding or alighting and 5 percent had fallen off a station platform.

Many ambulant less able people as well as people in wheelchairs are seriously limited in the distance they can walk or travel in a wheelchair. Access can be prevented by distance, slopes and road crossings as well as by the normally recognized curbs, steps and poor surfaces. Pedestrians in general are afraid of being attacked, being hit by a car or falling. ITS has considerable potential to help less able pedestrians, particularly with road crossings and with orientation for visually impaired people, thus minimizing pedestrian-vehicle conflicts (see Table 3).

**TABLE 3.**  
**Pedestrian Safety Problems and ITS Equipment**

Impairment	Problems	ITS equipment
Everybody	Crossing roads	Crossing signals that extend crossing time for slow pedestrians and/or warn drivers of pedestrians on crosswalks
Visual	Crossing roads	Audible signals at crosswalks Hand-held navigation system
Everybody	Falling on uneven pavements	Pavement condition monitoring Hand-held fall detector/Mayday system
Visual	Walking into traffic	Hand-held navigation system
Visual	Accidents: walking into plate glass, falling off platforms, steps	Hand-held navigation system

In Canada, 32 percent of fatal accidents to pedestrians involve people aged 65 or more; in Britain, nearly half of all pedestrians killed on the roads are over 60. The timing of road crossings is usually based on a pedestrian walking faster than many elderly or ambulant less able people can walk. Fear of being caught by traffic while crossing roads limits mobility and represents a clear lack of safety. In Britain, people detectors are being used to extend the length of the pedestrian phase when a slow-moving pedestrian is on the crossing. The same equipment omits the pedestrian phase if there is no pedestrian waiting to cross, even if the pedestrian button has been pushed. This avoids delaying traffic unnecessarily and increases respect for light controlled crossings. Pedestrian crossings can also be regulated by video cameras capable of distinguishing pedestrians from animals and cyclists and providing sufficient crossing time for individual pedestrians. Similar equipment can flash lights in the road surface to highlight the crossing when it is in use (Urban Transportation Monitor, 1996).

The greatest problem for visually impaired pedestrians is location and wayfinding. ITS should soon offer hand-held navigation systems using differential GPS. These could provide warnings of hazards plus instructions for the route to a selected destination (Gowda et al., 1995). Walking into traffick areas is another problem which could be helped by warnings from local beacons. An increasing number of elderly people suffer from dementias, such as Alzheimer's disease, causing them to become lost. If they are equipped with a portable transmitter they can be tracked and found, using

equipment similar to that used to track stolen cars or trucks.

## CONCLUSIONS

Elderly drivers have a high accident rate per kilometer driven, though not per person per year, and elderly pedestrians and users of public transport also have above-average accident rates. ITS has the potential to improve the safety and security of elderly and less able travellers and drivers, as well as to increase their mobility. For car drivers, various ATIS and AVCSS systems provide services or perform tasks that should make driving easier, less stressful and safer. Smart restraint systems could improve occupant protection.

Public transport users will be helped by smart cards and better information while travelling. These will reduce the need for passengers to hurry or to stand while the bus is moving, which reduces the risk of accidental falls. Their security can be improved by using real-time transit information to reduce waiting time at bus stops, particularly in bad weather, and by automatic vehicle location and communications to call for assistance when incidents occur.

Pedestrians can be helped by better road-crossing facilities, making use of existing people detectors. Pedestrians with visual impairments can be helped by hand-held location and guidance equipment, by talking signposts and by information displays that can talk when triggered.

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# EVALUATION OF ACTIVE SAFETY PERFORMANCE OF MAN-VEHICLE SYSTEM

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## ABSTRACT

Human factors have been found to be the major cause of vehicle accidents. We studied the driver-vehicle closed-loop system. Using the motion-type driving simulator the active-safety performance of 100 ordinary drivers was examined for two conditions : obstacle avoidance and slippery curve control. From the resulting data a computer model was developed. After confirming the validity of the computer model, the active-safety performance of drivers under the two conditions was better understood and in the case of the slippery curve condition, driver assistant devices are feasible.

## INTRODUCTION

In future transport systems, driver/ vehicle/ environment interactions are major issues in the active safety of vehicle operations. Almost all the causes of accidents are related to human factors involved in the driver's maneuvers: Recognition, judgement and operation. Improving the maneuverability of vehicle is urgent problems for vehicle-based technologies like collision avoidance systems. In this field of studies, it is indispensable for discussing the point of view of man-in-the-loop to consider active safety performance of vehicle.

Concerning to these problems, there are many prior studies about driver's behavior analysis with proving ground tests and driving simulators. The mathematical maneuver's modelings were also proposed for various driving situations from the results of the analysis. Under these considerations, it would be more important to obtain the ordinary driver's performances as well as expert drivers. The compromization with the driver's maneuver and the operation of vehicle would realize the real vehicle safety.

In this study, taking driver-vehicle closed loop into

account, active safety performances of the system were analyzed in emergency situations. At first, under such critical conditions like sudden emerged obstacle avoidance, ordinary driver's avoiding maneuvers were examined using a motion-type driving simulator. According to the driver's maneuvers in various emergency conditions, a database of driving operational characteristics was constructed and a mathematical model of driver's operation was also derived from these data. By computational simulation with driver/vehicle closed loop model, the performance of the system was predicted. The agreements with predicted performance were verified from experimental results. Especially in the case of curved road running condition, assuming the sudden change of road surface to a slippery situation, the effect of an "assistant control of steering" was estimated from both the model simulations and experiments by the driving simulator.

## EMERGENCY AVOIDANCE EXPERIMENTS

### Experimental Procedure

The driving simulator used in this study is illustrated (Figure 1.). The simulator is constructed with the moving base of two degrees of freedom, namely roll and lateral motions. On the moving base, the systems are mounted with driving cockpit and visual screen. Driving seat is installed in the half-cut vehicle body and the visual scenes given by computer graphics systems according to the driver's operations. Both of the motion and visual systems are controlled by computational vehicle model driven by the driver. The projected visual angle is 60 degrees wide at the screen located in 2.5 m ahead from the driver. Inside the cockpit, there are equipped imitating systems for steering reactions and induced small vibrations and interior noise corresponding to the state of the running conditions.

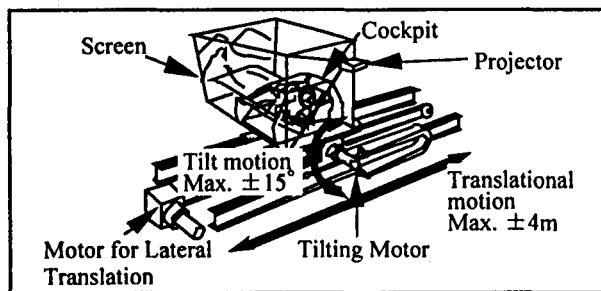


Figure 1. Driving Simulator.

The motion base is moved laterally by chained belts along the pair of lateral rails and rotatively by another motor installed in the bottom of the cockpit. In the systems, the lateral motion is controlled proportionally by the calculated lateral displacements of the vehicle model and the rotational motion is also controlled according to the centripetal acceleration by the vehicle speed and the road curvature of supposed situations. Using these equipments, driver's behaviors and vehicle performances are measured quantitatively in the same time.

The vehicle model used in the simulator has three degrees of freedom, namely longitudinal and lateral and yawing motions. The tires are modeled by Magic-Formula equation with combined status of lateral and longitudinal acting forces. The vehicle dynamics is calculated by personal computer from the input signals of the driver, accelerator pedal stroke, brake pedal stroke and steering wheel angle. The calculation interval of vehicle dynamics is 10 milliseconds.

Two kinds of experimental tasks for emergency avoidance are examined. One is a sudden emerged moving obstacle during running on the road and another is an unexpected slippery surface during curve running (Figure 2.). These tasks are supposed to be ordinary road and indicated vehicle speed is about 60 km/h for each subject. The experimental subjects are all ordinary drivers, and the number is 100, including 20% female drivers and the age from twenties to fifties

### Driver's Maneuvers in Emergency

Driving behaviors were examined by imitating obstacle emerging behind walls and surface change on

curved road. From the results of obstacle avoidance, the database of driver's operational characteristics depended on the modes of maneuver is constructed. The modes of avoidance are divided into associated operation of braking and steering and single operation. Averaged values of each steering and braking maneuvers are also shown (Table 1.).

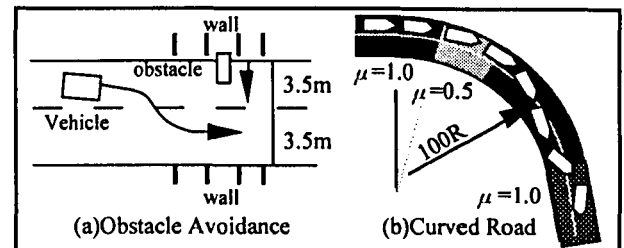


Figure 2. Experimental Situations for Emergency Avoidance.

Table 1.  
Characteristics Values of Driver's Maneuvers

modes of maneuver	success /fail	steering maneuvers			braking maneuvers		
		r sec	$\delta$ max	$\delta$ max	r b	Tb sec	Bs %
total panel's operations	all	0.72	355	104	0.74	0.39	65
	s	0.73	372	121	0.69	0.36	67
	f	0.70	333	85	0.78	0.41	63
case of associated operation	s	0.70	369	132	0.70	0.37	64
	f	0.72	316	101	0.76	0.40	62
case of single operation	s	0.55	378	102	0.63	0.36	80
	f	0.59	421	111	0.80	0.42	65

r : Steering reaction time(sec)  
 $\delta$  max : Maximum steering velocity(degree/sec)  
 $\delta$  max : Maximum steering angle(degree)  
 r b : Braking reaction time(sec)  
 Tb : Braking time const(sec)  
 Bs : Braking stroke(%)

The examples for individual operational characteristics are histogramically shown (Figure 3.). From these database, the difference of reaction time between the case of success and fail (collision) and the amount of each operation are clarified

Next the observation of driving managing behaviors in curved road leads to the relation between reaction time and steering velocity in the case of slippery region (Figure 4.). From the result, the reaction time is distributed in the center of 0.7 seconds after encountering slippery surface and the maximum steering velocity is distributed around 400 degree/s. In that case, the driver's maneuvers are depended on the individual situations and their experiences. In these



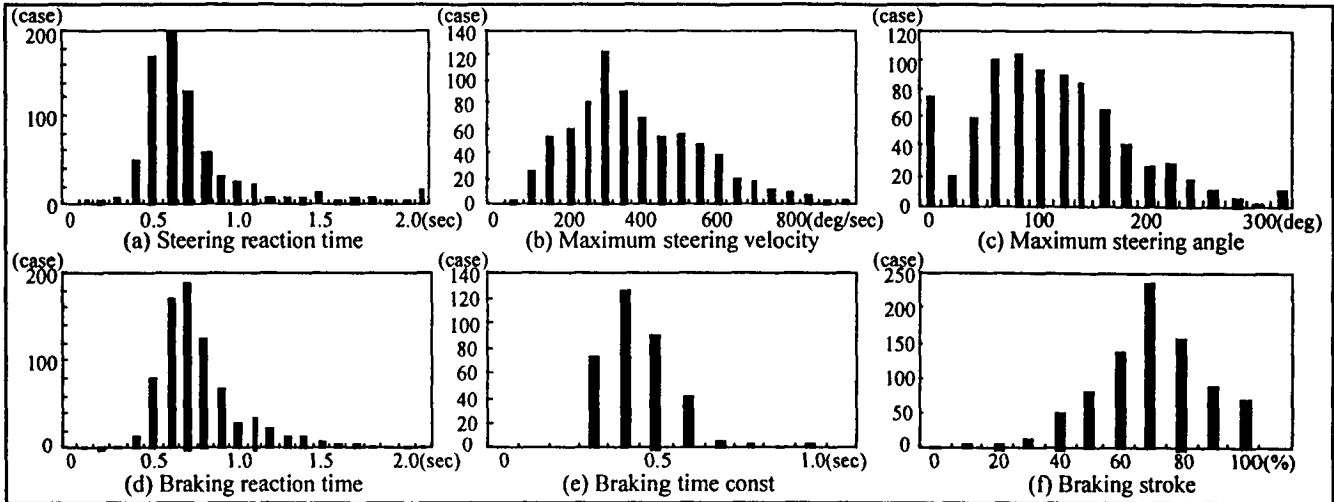


Figure 3. Examples of Driver's Maneuvers.

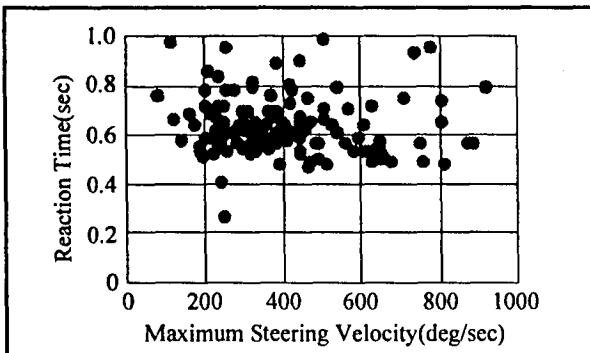


Figure 4. Reaction Time and Steering Velocity on Curved Road Management.

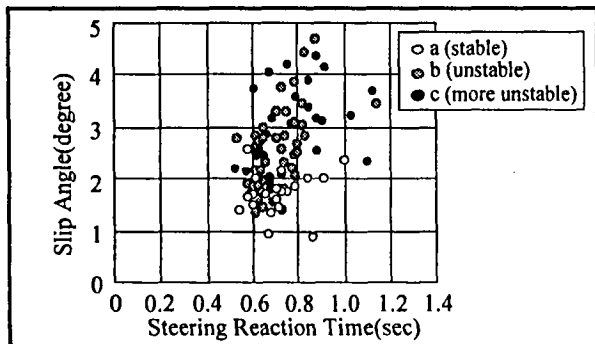


Figure 5. Steering Maneuver and Slip Angle of Vehicle.

cases, managing behaviors are classified into three cases, road-departure towards inside of the road, outside and divergent scattering. The reaction time seems to be depended on slip angle of the vehicle (Figure 5.). The driver

manages the vehicle inclination along the progressive direction noticing the change of road surface. The amounts of the data points of scattering are depended on the slip angle of the vehicle. Thus each driver manages his maneuvers consulting with a man/vehicle system in such a critical situation.

## DRIVER'S BEHAVIORS MODELING AND PERFORMANCE EVALUATION

### Driver Operating Model

Mathematical driver operating model is derived from experimental data of above mentioned situations. The model is constructed with steering (lateral control) and the braking (longitudinal) operation.

The parts of steering operation are based on the variable preview time and variable preview point. These are constructed by the three parts, prediction, target course generation and steering control block. In the prediction block, it is assumed that the driver involves the simple vehicle model and predicts the future vehicle position and vehicle state values. In the target course generation block, driver's operating model generates the course of before and after the obstacle emerging. In the steering control block, steering angle is derived as a type of integral control that minimizes the both of corrected steering angle and the deviation

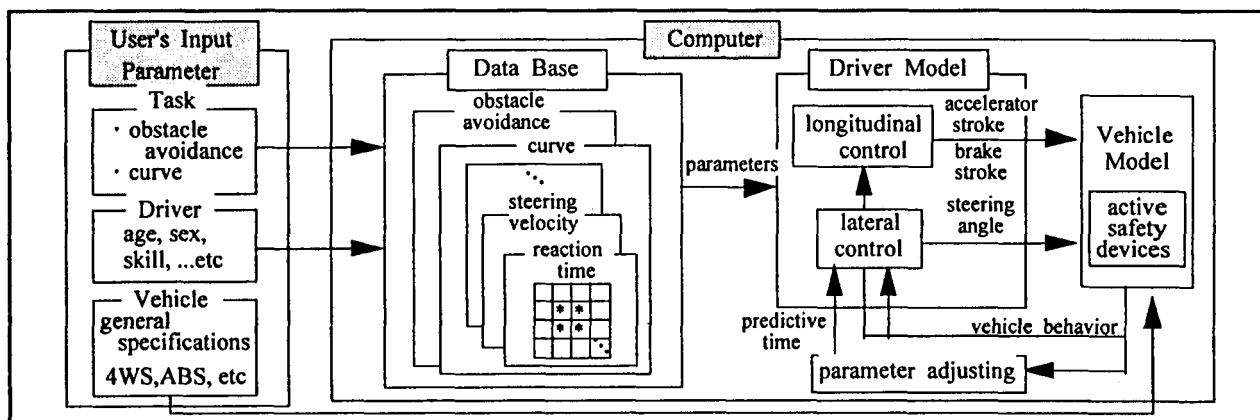


Figure 6. Schematic Diagram of Driver-Vehicle Performance Evaluation System.

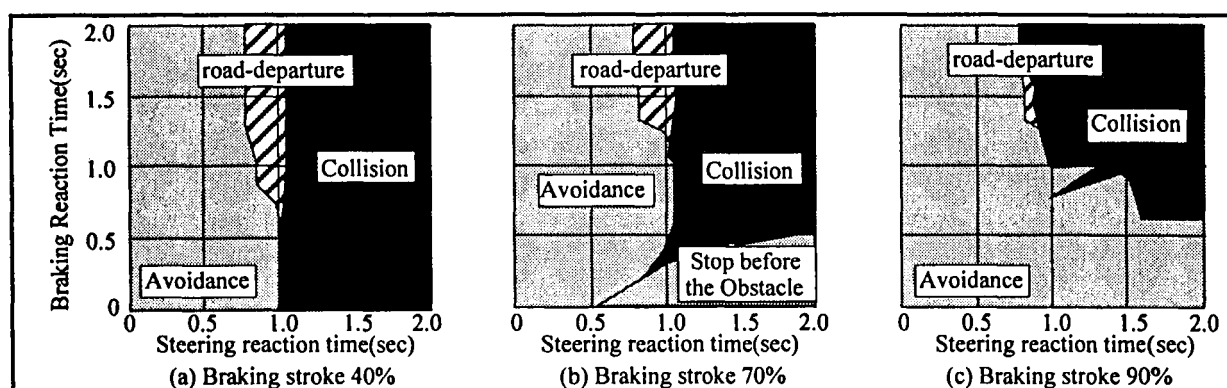


Figure 7. Obstacle avoidance performances due to driver's maneuvers.

between generated course and predicted course.

The braking operation is expressed with the first order delay system with lag time from the basis of experimental results. Here, the lag time is equivalent to the braking reaction time. The gain of the first order delay system is the maximum brake pedal stroke. The time constant value corresponds to the time from the beginning of braking operation to reach the maximum brake pedal stroke.

Combining the driver model and vehicle motion model, using the database, driver-vehicle performance is calculated for various tasks (Figure 6.). The block diagram is shown from user's input parameter as supposed road, selecting data and calculating the models, to the last part of vehicle performances on the emergent situations.

### Avoiding Performance Estimation

The obstacle avoidance performance is estimated by

the simulation as below. In the case of emerging obstacle, supposing vehicle speed is 60 km/h, the gap length to the obstacle is 40m in time of obstacle start to emerge, the avoiding performance is evaluated for associated behaviors with braking and steering. The driver's skill is supposed to be below the averaged, namely maximum steering velocity is 200 degree/s. The obstacle avoidance performance is shown with braking stroke as the functions of brake and steering reaction time (Figure 7.). The performance is classified to three patterns ; avoidance, namely success to avoid the obstacle, the collision to the obstacle and the road-departure from the road edge. The figure shows the influence of avoiding ability concerned with both of brake and steering reaction time. The drivers who operate in larger steering reaction time than 1.0 second would come into collision to the obstacle. On the contrary, even if for rapid steering, delayed braking action over 0.8 second leads to the road-departure from the road edge. According to the amount of

brake stroke, the avoiding ability would be increased with the stroke and braking assistance and these system would be effective for poor power drivers.

### Managing Performance Estimation

Another emergent situation is sudden surface change to slippery condition during curved road. In the case that surface is changed from 1.0 to 0.5 in rear wheel, supposing vehicle speed is 70km/h and the curvature of the road is 100m, the managing performance of the vehicle is evaluated in three kinds of steering reaction time (Figure 8.). In these cases, the prediction time in the driver model is supposed to be changed from 0.7 to 0.5 second before and after the low frictional area.

The estimated results are shown in the figure that there are three patterns for managing performance on slippery curved roads. These phenomena is also derived from the driver-vehicle active safety performance.

### VERIFICATION OF DRIVER'S ASSISTANCE BY STEERING CONTROL

Driver's assistance in emergent situation would be of necessity to improve driver-vehicle closed loop performance. Supposing the assistant steering controls, the effect of the controls on the performance were estimated. Calculation conditions were the same with Figure 8. In the case of without control X, with differential steering control Y and with yawrate feed back control Z, the estimated vehicle trajectories, steering angles and front steer angle at that time are shown (Figure 9.). From the results, every controlled case is effective for preventing the divergent phenomena of the vehicle after entering the low frictional area. The controlled case is stable in the trajectory of the vehicle and would be estimated to stay within the lane.

Next, supposing the similar control system into the vehicle model of the driving simulator, the driving behaviors in the imitated environmental conditions are examined for several subjects. The results are shown in the vehicle trajectories and steering angles at these occasions (Figure 10.).

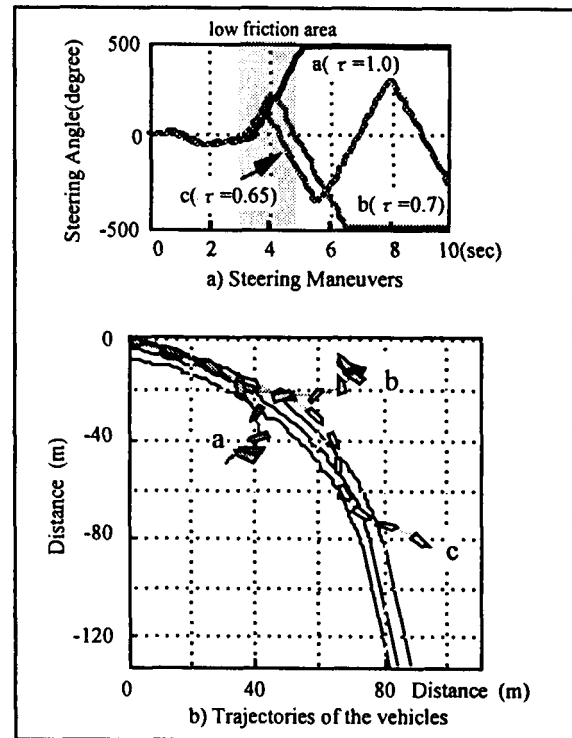


Figure 8. Simulation Results for Different Reaction Time.

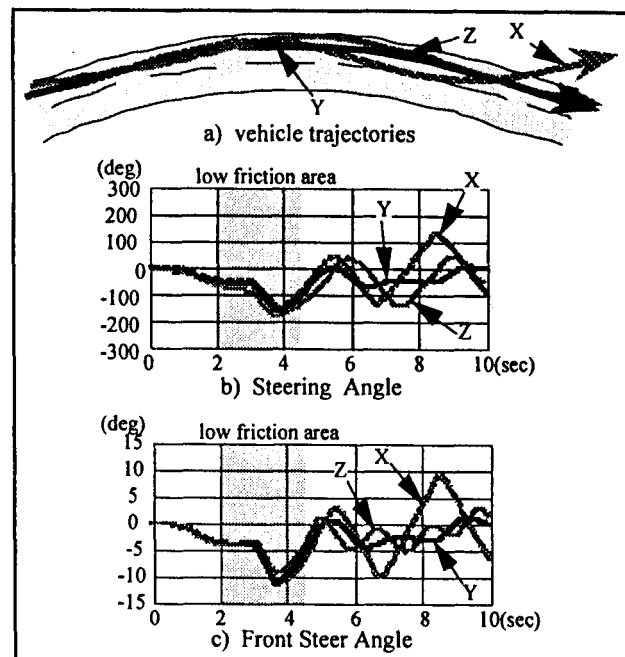


Figure 9. Simulation Results for Steering Control.

Comparing with the experimental results and the estimated behaviors, the trajectories of the vehicles were very similar with each other and steering maneuvers were well improved. The subjective judgements of the drivers were better for steering feeling and the recovery of vehicle direction was fairly improved. Thus the driver managing performance of the emergent situations was evaluated with estimation of the effect of assistant steering control.

## CONCLUSION

The avoiding behaviors are examined for ordinary drivers in emergent situations using driving simulator. From observations of the maneuvers, the mathematical driver model is derived and the active safety performance of driver-vehicle system is discussed from both of the computer simulations and the simulator experiments. The features of evaluation methods in this study are summarized as followings.

- (1) Supposing two kinds of emergent situation, characteristics of avoiding maneuvers are examined and the database is constructed for ordinary drivers. The reaction times of braking and steering in emergency avoidance, the operational velocities, and the amount of each action are classified. The averaged values for each are obtained finally.
- (2) Computational analyzing system for driver-vehicle performance is constructed with the experimental database of operational maneuvers and vehicle performance model including driver's operations. Regarding the change of

curvatures, surface conditions and driver property as well as vehicle characteristics, the vehicle motion road performance is evaluated as the results of driver's emergent operations and the vehicle responses.

(3) Using the analyzing system, avoiding performance in sudden emerging obstacle and managing performance in slippery curve running are estimated. These results are shown to be effective for evaluating the active safety performance of driver-vehicle system.

(4) Applying the evaluation methods to driver aid devices, the effect of driver's assistance by steering control is predicted with the computational estimation and verified from the driving simulation experiments.

Finally taking these evaluation methods, it should be more effective and adequate for designing the driving safety devices to make a better human interface to future transport systems.

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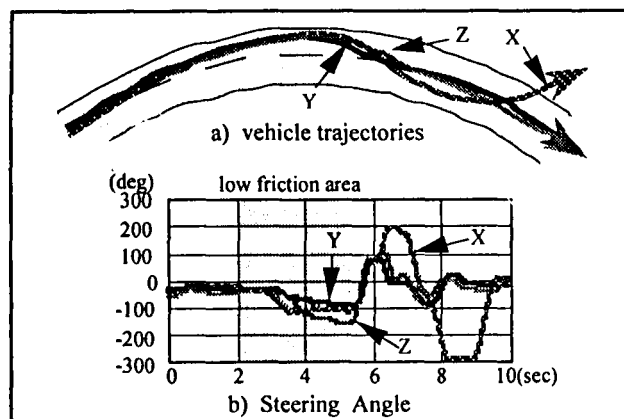


Figure 10. Experimental Results for Steering Control.

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# RELATIONSHIP BETWEEN DRIVING BEHAVIOR AND TRAFFIC ACCIDENTS - ACCIDENT DATA RECORDER AND DRIVING MONITOR RECORDER

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## ABSTRACT

A field trial has been carried out using a set of automatic recording system, Driving Monitoring Recorder (DMR) and Accident Data Recorder (ADR) installed on 20 vehicles in a fleet of cars in Tokyo area, in order to assess the implications in driving behavior and accidents. The 38 subjects, who drive the 20 vehicles were monitored during driving by the DMR for one year. Simultaneously, the data in pre- and post accident were recorded by ADR whenever accidents occurred. In addition, the drivers were examined by a driving aptitude test.

The data by DMR are analyzed focusing on fluency of occurrence of emergency brake operation and/or rapid start performance as representing driving behavior as a trial.

The 23 accident cases including cross accident, rear-end accident, turning accident, are collected by ADR for one year. The accident data are analyzed focusing on environmental condition in pre- accident stage and driving behavior.

Relationships between driving behavior and accident are proposed as results of data analysis. In particular, the accident mechanisms of specific accidents, in which the subject ranked careless driver involved can be explained in terms of driving behavior, which is determined by his cognition and/or judgment when he is facing specific environmental situations. A set of the automatic recording systems offer very clear benefits to study traffic accident mechanism in particular on the manner of driving immediately before accident,

and they will provide hitherto unavailable information in the field of road safety.

## 1. INTRODUCTION

For the prevention of traffic accidents, it is important to clarify the relationship between the traffic situation immediately before the occurrence of a traffic accident and the characteristics of individual driver. This mutual relationship, however, is so complicated that accident investigations conducted based on conventional investigation techniques and many inspections and studies made to identify the characteristics of drivers have scarcely succeeded in clarifying it.

Driver education requires that information on these key factors leading to a traffic accident be informed to drivers in a concrete and specific manner. In this driver education, however, information on how traffic accidents occur through this complicated mutual relationship between the traffic situation and drivers' characteristics is provided only briefly and insufficiently; more practical driver education techniques need be developed. The previous report described the effectiveness of the technique of collecting data on the behavior of drivers just before the traffic accidents by using automatic recording systems.(1),(2),(3)

In the paper, the accident data recorder and driving monitoring recorder are installed on commercial vehicles and collected, and analyzed data. Specifically, the accident data recorder was used to collect physical data at the occurrence of traffic accidents, i.e., the change in speeds, impact acceleration, the state

of braking and lighting, etc., just before the traffic accidents and the driving monitoring recorder was used to collect data on the everyday behavior of drivers, i.e., road speed, the frequency of rapid starting and sudden braking, etc.

In this report, one traffic accident that a certain driver encountered is taken up and the situation in which this traffic accident occurred is analyzed in full detail, focusing on the relationship between the traffic situation and the behavior of this driver. The results of this analysis indicate that they can be used as practical data for driver education. The outline of this analysis is described in the following chapters.

## **2. AUTOMATIC RECORDING SYSTEM**

### **2.1 Accident Data Recorder**

The accident data recorder (ADR: UDS2156) is the in-car recorder developed by MANNESMANN KIEINZEL which records and stores in memory on speed, longitudinal and lateral acceleration, yaw angle, brake activation (on/off), left and right direction indicators (on/off), plus six or so on/off channels.(3),(4),(5) While a vehicle is being driven, data, sampled at 500Hz, is stored in temporary memory where it is continuously analyzed by the accident detection algorithm. When the algorithm recognizes the characteristic features of an accident, the previous 30s and after 15s of data is transferred in coded form to a permanent memory. After data is stored, this recorder stands by, waiting for the next collision. It can record data on the first and second collisions.

### **2.2 Drive Monitoring Recorder**

The driving monitoring recorder (DMR: YAZAC-5064)(6) is the in-car safety driving recorder developed by YAZAKI METER Co., Ltd. It was developed as a recorder capable of monitoring the conditions of everyday traveling of vehicles. All other travel conditions such as running speeds, travel distance etc., are recorded as digital data. The data may be informed an important clue to identify and

appreciate the behavior of drivers from view of safety driver.

## **3. METHOD**

### **3.1 Data Collection**

The accident data recorder and driving monitoring recorder were mounted on 20 commercial vehicles. The accident data recorder tracks the vehicles on which it is mounted. On the other hand, the driving monitoring recorder tracks the drivers of these vehicles on which it is mounted. A 20 regular drivers were selected for 6 months, and after 6 months another group of 20 regular drivers were selected as subjects. The actual number of subjects selected this way, however, was 36 for reasons related to the combination of vehicles and drivers.

Each subject carries his own identification card; he inserts his card into the driving monitoring recorder each time he gets on a vehicle and pulls the card out when he goes off duty. Each card had a capacity of 65 KB and was withdrawn every two weeks to be integrated into a collection of actual records.

Data on all accidents that these 20 vehicles encountered during the twelve-month period were collected. The accident data recorder (ADR) can record data on two traffic accidents that occur successively. To verify whether these two successive traffic accidents are recorded as two successive events in the accident data recorder, it is necessary to check the operating conditions of this recorder. In the experiment, a line of communication was established beforehand so that data on accidents that occurred could be collected immediately. After all data were collected, the accident data recorder was automatically set back in service, getting itself ready to handle the next traffic accident.

### **3.2 Driving Behavior**

Figure 1 shows an example of data collected by DMR (This data is from an accident later described in Figure 2). The change in speeds and all other travel conditions

are recorded. It is possible to analyze and/or calculate how many times of the speed limit is exceeded, the number of times of rapid starts and sudden braking according to a definition rate.

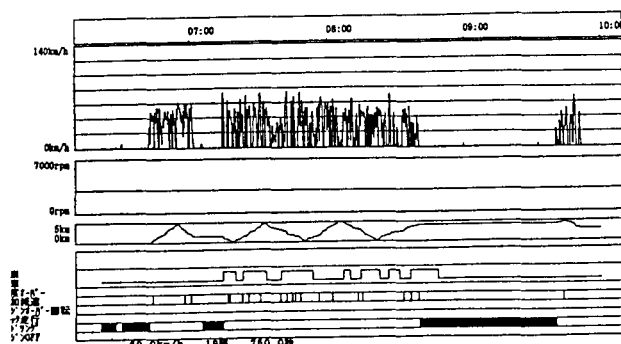


Fig.1 An Example of DMR Data

Based on DMR data collected, the number of times of sudden braking (exceeded by  $3.75\text{m/s}^2$ ), rapid acceleration and starting (exceeded by  $3.00\text{m/s}^2$ ), and the frequency of them per 100 km were analyzed. As an attempt to assess the driving characteristics of each subject objectively, the safety diagnostic indicators (radar chart) shown in the following were studied.

Specifically, the frequency of sudden braking, rapid starts and hard acceleration, speed distribution, the ratio of travel distance under loaded condition to that under unloaded condition (the loaded condition means traveling with a passenger and the unloaded condition means traveling without a passenger), economic efficiency, etc., were selected as elements for the assessment of driving characteristics. Values of these elements were recorded for all subjects and they also were calculated to obtain average values.

With these averaged values defined as 100, recorded values were plotted to make a radar chart; in other words, data on each individual subject was processed in a way that it could be represented on the basis of specified benchmarks and be plotted as indicators to make a chart as shown in Figure 2. This radar chart allows the identification at first sight of how each subject's driving characteristics differ from the overall average.

Unsafe driving behavior requiring special attention, a much greater frequency of sudden braking, for example, or overall driving characteristics of each subject can be identified by simply viewing the shape of this chart. Detail data analysis is now under consideration.

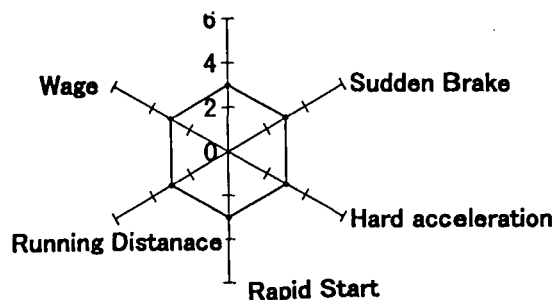


Fig. 2 A Radar Chart represented Driving Characteristics.

### 3.3 Accident Data

A 20 Data obtained by ADR, specifically, data on 13 different cases were analyzed in full detail. Further, in order to identify a mechanism of the traffic accidents based on the results of accident data analysis, we went to the actual site where a traffic accident occurred to verify the road conditions and to make various site surveys. We used data obtained this way to relate it to the driving behavior (speed, the state of acceleration and deceleration, braking, operation of direction indicators, etc.) just before the occurrence of the traffic accident.

## 4. RESULTS

### 4.1 Evaluation Driver Behavior

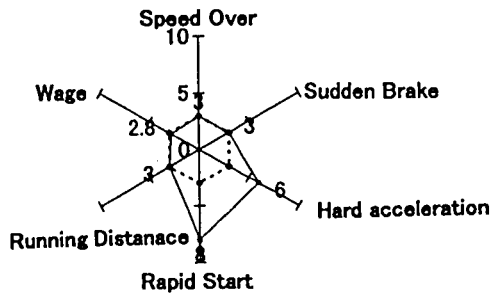
Data on the driving behavior of drivers collected with the driving monitoring recorder over a period of about one year were evaluated, focusing attention on the number of times of sudden braking and rapid starts and distance traveled. Table 1 shows the results.

Figure 3 shows the radar chart represented driver behavior on driver A. He is characterized as careless driver because driving behavior with high frequency of rapid braking, start and acceleration.



**Table 1 An Example of Result of Driving Behavior by DMR.**

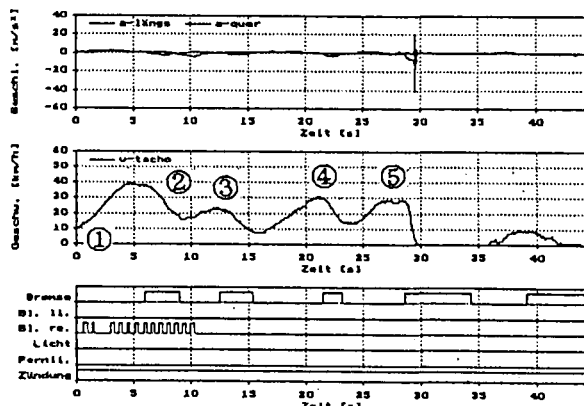
subject	frequency of them per 100 km			
	acceleration	starting	braking	starts
A	20.57	40.36	3.09	302
B	2.12	1.32	1.59	424
C	2.23	14.35	1.59	128
D	13.99	13.03	15.26	522
E	16.33	13.36	3.86	369



**Fig. 3 The Radar Chart represented Characteristic of Driver "A"**

#### 4.2 An Example of Traffic Accident Data

Figure 4 shows an example of data on traffic accidents collected by ADR. The data is raw data acquired by the recorder showing the change in speeds and state of braking during the period of 45 seconds just before and after the occurrence of traffic accidents. As is evident from this figure, the operation of data storage starts in response to the front-to-back (and side-to-side) impact acceleration which occurred just short of the 30-second point (called a trigger point) along the abscissa axis.



**Fig.4 The Accident Data occurred by Driver "A".**

As shown in Figure 4, the change in speeds can be verified as follows:

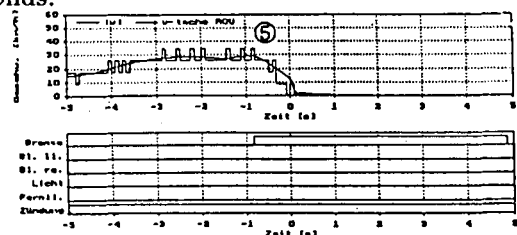
- (1) The vehicle that caused the traffic accident increased the speed for about four seconds, starting at about 10 km/h, and reached 40 km/h. During all this time, the right direction indicator remained on. As it reached 40 km/h, it slightly decreased the speed for about 2 seconds and continued running by maintaining this decreased speed, and
- (2) it decreased the speed to about 17 km/h by braking, and then
- (3) it increased the speed to about 23 km/h and immediately slowed down by braking. After repeating this cycle of decreasing and increasing the speed twice, it reached the site of the traffic accident.

This driving situation can be interpreted as follows:

The driver increased the speed from 10 km/h to 40 km/h while keeping the right direction indicator on, that is, turning the vehicle right. As he reached 40 km per hour, he decreased the speed (about  $1.8 \text{ m/s}^2$ ) by braking. Then he repeated a cycle of increasing the speed and decreasing speed by braking to reach the target speed of about 30 km/h. This indicates that he was driving carefully.

Under what traffic situation did he drive his vehicle this way? Why did the traffic accident occur though he drove carefully? We analyzed data in more detail to understand the situation just before the occurrence of the traffic accident as follows:

- After the step (3) mentioned earlier,
- (4) after the vehicle reached approximately 30 km/h, it immediately decreased the speed,
- (5) it again reached about 30 km/h and maintained this speed for approximately 3 seconds.



**Fig.5 The Accident Data around Collision occurred in Figure.4.**

In Figure 5, data are expanded with the trigger point (0) as the center of expansion. That is, the brake was applied immediately after the vehicle maintained the speed of about 30 km/h for about 2 seconds. At the point about 0.8 second after the brake was applied, the collision occurred.

When this collision occurred, the vehicle's speed was about 12 km/h. Right after this collision, the wheels were locked and a reading on the speedometer was 0. It is also noted that the driver continued to step on the brakes for 5 seconds after this collision.

It is estimated that the brake was applied a little too late but why? Is it simply the matter of a little slow reaction on the part of the driver? Is it related to this particular traffic situation?

In Figures 6 and 7, the traffic situation of the accident site is shown. The accident site is in the typical downtown area of Tokyo where a narrow one-way road crosses another narrow road. In Figure 6, the route that the vehicle followed right before the occurrence of the accident is shown. This one-way road is used as a detour that allows drivers to enter from the main street (A), go through eight small crossings and get on the main street (B) which leads to the heart of Tokyo about 230 m away from where this one-way road meets the main street (B). In Figure 7, photos of a intersection with traffic lights and the crossing where the accident occurred are shown. The crossing where the accident occurred is the third crossing.

This crossing is the only crossing where the one-way road leading to the main street (B) crosses a two-way road. Considering that this one-way road crosses other one-way roads at all other crossings, this particular crossing is estimated worth special attention.

With reference to data on this traffic accident shown in Figures 4 and 5, the behavior of the vehicle that caused the traffic accident can be analyzed according to Figure 6 as follows:

- (1) the vehicle in question running at the speed of about 10 km/h increased the speed just short of the intersection with

traffic signal lights of the main street (A). With the right direction indicator turned on, it approached the crossing that had traffic lights. At this time, it increased the speed to 40 km/h.

- (2) just short of the crossing that had traffic lights, it decreased the speed to about 17 km/h by braking and turned right at the crossing and entered the one-way road (speed limit: 20 km/h).
- (3) over a distance of about 50 m short of the first crossing, it slightly increased the speed. As it was approaching the crossing, it decreased the speed to about 9 km/h by braking.
- (4) over a distance of about 30 m short of the second crossing, it increased the speed to 30 km/h. Just short of the crossing, it decreased the speed to about 15 km/h by braking.
- (5) Over a distance of about 30 m short of the third crossing (where the accident occurred), it increased the speed according to the same pattern of driving behavior and approached the crossing. It seemed to decrease the speed as it did when approaching the crossing mentioned under (4) above but it actually did not decrease the speed; it kept on traveling at the speed of about 30 km/h for about 2 seconds.

There is similarity in the behavior described based on each specific distance traveled to each crossing. As Figure 5 indicates, however, after it reached the speed of approximately 30 km/h, the brake was applied 1.5 to 2 seconds later when approaching the third crossing (where the accident occurred) than when approaching the first and second crossing. Figure 8 shows the relationship between distances from the point of collision as a base point and speeds at each distance. That is, it is found from Figure 8 that the speed was increased at the point 10 m short of the point of collision.

The speed and time in Figure 5 indicate that the vehicle was approaching the crossing where the accident occurred while starting to increase the speed at the point approximately 5 seconds before the collision. After it reached

the speed of about 28 km/h, it decreased the speed for an instant. Because the driver did not step on the brakes at this moment, it is estimated that he released the accelerator pedal and consequently the speed decreased for an instant. Then the driver depressed the accelerator pedal and the speed increased, which indicates that he intended to pass through the crossing without decreasing the speed.

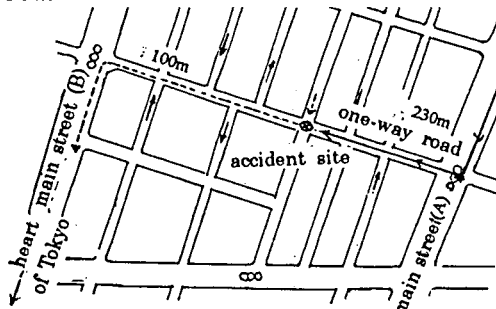


Fig.6 The Plan of Accident Site.

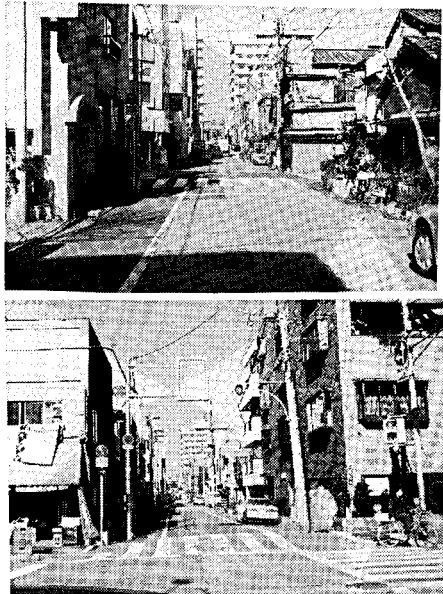


Fig.7 The Scene of Accident Site.

Judging from the fact that the vehicle collided with the back of the other vehicle entering the crossing, the driver of the vehicle in question could not see the other vehicle approaching the same crossing because the wall of a house in the corner interrupted the view. That is, it is presumed that the driver of the vehicle that caused the accident tried to pass through the crossing while increasing the speed without checking the entry of the other vehicle to the crossing.

What matters here is the driver's judgment. Why did he enter the crossing though he recognized the other vehicle entering the same crossing?

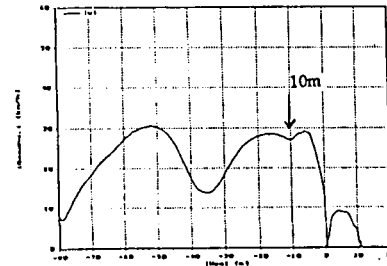


Fig.8 The Speed vs. Distance around Collision occurred.

The first point that need be considered is that this vehicle was traveling on a one-way road which was given the right of way. On the other hand, the other vehicle was traveling on a road with the stop-and-go sign which does not have the right of way.

This awareness of the right of way is thought to be a possible cause of the accident; more specifically, the driver recognized the other vehicle with awareness of the right of way given to the road he was traveling on and reconfirmed in his mind that his vehicle had the right of way over the other vehicle.

This inference may not be well convincing because it cannot account for the behavior of decreasing the speed when approaching the first and second crossings.

The next inference is that the driver intended first to let the other vehicle pass through before his vehicle and then to pass through himself by going directly behind the back of the other vehicle. To do this, he adjusted the speed at the point 10 m short of the crossing. He made a mistake, however, in adjusting the speed and collided with the back of the other vehicle.

In this case, it is presumed that the driver would try to pass behind the other vehicle and to turn the steering wheel to the right. In reality, however, the vehicle behaved just before the collision as shown in Figures 11 and 12, that is, the driver turned the steering wheel to the direction where the other vehicle was proceeding, i.e., he turned it to the left.

Considering these two inferences, the former inference seems to better explain the base of the judgment made by the driver; the driver decreased the speed about 12 m short of the crossing as he did when approaching the second crossing but he judged at the point about 10 m short of the crossing that no vehicle would enter the crossing.

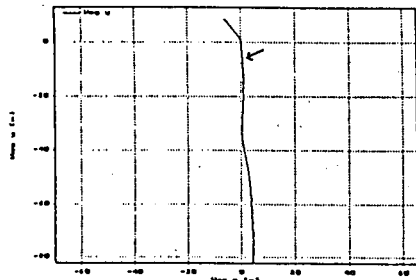


Fig.11 Trajectory of Vehicle Behavior.

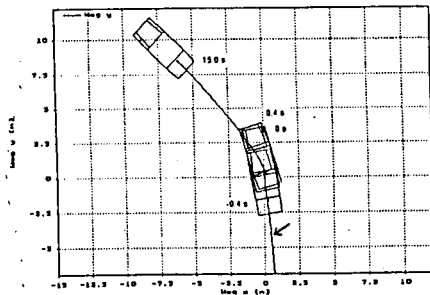


Fig.12 Vehicle Behavior around Collision Point.

In addition to this judgment, he was aware of the right of way given to the road his vehicle was traveling on and also he had experience of driving to the main street (B) (about 130 m ahead) in the same traffic situation. More specifically, he judged that no vehicles would enter his way because three of the remaining four crossings were all T-junctions. It is thought that on this judgment he adjusted the speed to cope with the state of traffic signals on the main street and tried to pass through the crossing where the accident occurred as quickly as possible

## 5. DISCUSSION

### 5.1 Accident and Situation

Although data just before the accidents can be collected with the accident data recorder, it is difficult to explain the traffic accident occurrence mechanism unless

investigations are pursued to the level where the psychological aspect of drivers' behavior is elucidated. We can safely say that we must further develop the studies in the behavior of drivers through continued effort to collect and analyze data. One thing can be clearly pointed out here: drivers' awareness of the traffic situation is closely associated with the occurrence of traffic accidents. In this particular case, the driver knew that all crossings ahead of the crossing where the accident occurred were T-junctions and that he could drive this distance of about 100 m in a stable smooth manner. Furthermore, it is presumed that still other situation-specific elements affected the driver's behavior, namely, he could see the status of traffic signals at the entry to the main road from a distance and, therefore, he could possibly adjust his speed to have his vehicle slide into the main road smoothly. All in all, the present study suggests that data collected with the accident data recorder can be used effectively to conduct practical studies in the correlation between the traffic accidents and the traffic situation from various angles.

### 5.2 Relationship between Data of ADR and DMR

According to data collected by the driving monitoring recorder, this driver who caused the traffic accident is identified as being the driver "A" (shown in Table 1) who practice hard acceleration and rapid starts with much greater frequency than other drivers.

Even greater volumes of data are required to study the relationship between the driving behavior under a normal driving situation and traffic accidents and, at the same time, various studies need be conducted to identify how such volumes of data can be analyzed.

The relation with the conventional driver aptitude test in particular is now listed as one of subjects that require studies. The results of the present study indicate that a high frequency of sudden braking and other types of driving behavior generally considered the

factors of ineligibility as a driver can be one of the indexes to identify the characteristics of drivers.

### 5.3 DMR Data for Safety Education

Data collected with the driving monitoring recorder shows detailed information on individuals' everyday driving and can possibly be used to point out dangerous ways of driving objectively and improve them.

Four subjects were interviewed and results of analysis made on their individual driving data were shown to them. They were advised to improve their driving behavior with respect of two to three driving deficiencies, a greater number of times of sudden braking, for example. Explanations were given as to how the driving monitoring recorder is monitoring their driving behavior at all times and that drivers are required to be well aware of their deficiencies and to have the positive attitude to improve themselves.

The number of driving deficiencies pointed out to each driver is limited to only two or three which may be the limits he can manage to improve at one time. Also such driving deficiencies to be pointed out are limited to the type of behavior that is obviously considered an unsafe driving pattern, such as sudden braking. Also each driver's attention was called to how different his driving data is from data of other subjects, so that each driver as a subject can have a good understanding of the characteristics of his driving behavior.

If it is possible to acquire data attesting to the possibility to improve the driving behavior of professional drivers by giving such simple instructions, the type of education based on data collected by the driving monitoring recorder will be considered worth notice and a new demonstrative approach to the safety education.

## 6. CONCLUSION

The present study demonstrates that data before and after the occurrence of a traffic accident can be recorded with the accident data

recorder and driving monitoring recorder and that a traffic accident can be reproduced in full detail, including the driving behavior just before the occurrence of a traffic accident. If it becomes possible to relate the results of this close investigation into the cause of a traffic accident to the characteristics of drivers' everyday driving behavior, this new approach to the driver education can be an important breakthrough in the prevention of traffic accidents. It is expected that this approach to the driver education based on the effective use of information collected by these automatic recording systems can be a powerful means of practical driver education and can offer convincing clarification on how and why traffic accidents occur through complicated combinations of drivers' characteristics and situation-specific factors.

## ACNOWLEDGMENTS

The authors would like to take this opportunity to express appreciation to Mr. A. Kast to analyze the data of ADR. The authors would also like to thank Mr. T. Ogino and Mr. K. Konishi collecting the data, and to thank Mr. K. Ohba offering some devices.

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# ANALYSIS OF THE CRASH EXPERIENCE OF VEHICLES EQUIPPED WITH ANTILOCK BRAKING SYSTEMS (ABS) -AN UPDATE

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## ABSTRACT

This paper updates the findings from initial analyses of the crash experiences of passenger cars (PCs) and light trucks and vans (LTVs) equipped with antilock braking systems (ABS). As before, separate analyses were conducted for PCs and LTVs, for each type of ABS system (rear and all wheel), for each of several crash types and each type of road surface (favorable and unfavorable). The present analysis also considers crashes involving pedestrians, in addition to the four crash types previously considered. The findings for passenger cars in fatal crashes for this study are very similar to the earlier results, i.e., for non-fatal crashes the benefits in avoiding frontal crashes remain about the same. Side impacts and run-off-road crashes on unfavorable surfaces, went from a predicted increase in the earlier study to non-significance in these findings. In addition, there are decreases predicted for crashes involving pedestrians.

## INTRODUCTION

Section 2507 of the Highway Safety Act of 1991 directed the National Highway Traffic Safety Administration (NHTSA) to initiate rulemaking to consider the need for any additional brake performance standards, including ABS, for all passenger vehicles, i.e., PCs and LTVs weighing less than 10,000 pounds. Meanwhile, automobile manufacturers have offered ABS to consumers either as a standard feature or as an option on millions of PCs and LTVs since 1985.

The objective of ABS is to automatically modulate braking pressure to prevent the vehicle's wheels from locking during braking. Two types of ABS systems are presently available: All wheel (AWAL) and rear wheel (RWAL). At the time of the earlier analysis, RWAL was much more prevalent in the on-road LTV fleet but AWAL is now becoming more available for LTVs. All PCs are equipped with AWAL and, therefore, only AWAL ABS was considered for PCs.

The focus of this study was to update earlier estimates of the impact of ABS using similar methods. As before, the impact of ABS on specific types of crashes considered to be "ABS relevant" was studied by examining the change in the proportion of crashes in which ABS had the potential to prevent the crash, assuming that the presence or absence of ABS does not affect the occurrence of nonrelevant crashes.

## DATA

Data from NHTSA's Fatality Analysis Reporting System (FARS) were used to analyze the crash experience of ABS-equipped and non-ABS-equipped vehicles in both the PC and LTV analyses. FARS, begun in 1975, contains a census of the most severe traffic crashes, i.e., those resulting in a fatality, occurring in the United States each year. FARS data for calendar years 1995-96 were used in the analyses. The earlier analysis used FARS data from 1989-93.

For both the PC and the LTV analyses, state crash files from Florida, Maryland, Missouri, and Pennsylvania for the period 1995-96 were also used. These states were chosen for study because each, for the period shown, recorded the vehicle identification number (VIN) for vehicles involved in crashes of all severities. The VIN was needed in order to identify specific makes and models of vehicles equipped with ABS and to identify comparable non-ABS equipped vehicles. The earlier analysis used state data for the period 1989-93.

For both the PC and LTV analyses, five types of crashes were identified as "ABS-relevant", i.e., crashes for which it was assumed that ABS would be beneficial in avoiding the crash and/or ameliorating the outcome of the crash. The four "ABS-relevant" crash types identified in the original study were: (1) rollovers, (2) side impacts with parked vehicles or fixed objects, (3) frontal impacts with parked vehicles or fixed objects, and (4) frontal impacts with another motor vehicle in transport. In the present update, pedestrian crashes, were added. Crash types (1) and (2) typically involve driver

loss of control. For these crash types, ABS is expected to increase the directional stability of the vehicle, allowing the driver to maintain greater control and remain on the roadway. Crash types (3) and (4), along with crash type (5), pedestrian crashes, typically involve driver loss of control or the presumption that the driver did not apply the brakes or was not able to stop in time. Both analyses examined the experiences for ABS and non-ABS-equipped vehicles in the ABS-relevant crash types, compared to a control group of crashes that were assumed to be unaffected by the presence of ABS. The control group consisted of crashes in which vehicles were struck while standing still or starting out after having been parked. In addition, the ABS-relevant crashes and control crashes were further classified based upon whether or not the crash occurred under "favorable" or "unfavorable" road conditions. Road surfaces that were paved, free of debris, and dry were considered "favorable." Road surfaces that were wet, snowy, icy, unpaved, or composed of gravel were considered "unfavorable."

## ANALYSIS

The basic approach was to study the change in the proportion of ABS-relevant crashes for ABS-equipped vehicles compared to non-ABS-equipped vehicles. Since the presence or absence of ABS could not be expected to be the only important factor in the crash, the analysis technique used must control for factors related to the driver, environment, or other crash characteristics.

Logistic regression, as described in Hosmer and Lemeshow, was chosen as the analytical method. This technique has been successfully used in other NHTSA studies. To accurately estimate the impact of ABS, variables were included in the logistic regression to control for those factors, other than ABS, which could influence the proportion of ABS-relevant crashes. For example, if ABS-equipped pickup trucks are more likely to be driven by younger males than by other segments of the driving population, then driver and vehicle characteristics could confound estimating the impact of ABS. To address this issue, variables representing the age and sex of the driver, whether or not the crash occurred on a curved road segment, whether the crash occurred in a rural setting or an urban setting, and the age of the vehicle were included in the logistic regression models. Using the state and FARS data, for favorable or unfavorable surfaces, for each type of ABS (AWAL or RWAL), for the four ABS-relevant crash types, a logistic regression model was estimated:

$$\text{LOGIT (P)} = \text{AGE YOUNG MALE CURVED} \\ \text{ABS RURAL}^* \text{VEH-AGE} \quad (1^{**})$$

where the data modeled include the particular ABS crash type response being analyzed and control crashes, P is the probability of an ABS-relevant response, AGE is the age of the driver, YOUNG is an indicator variable with the value 1 if the driver is under 25 years of age and 0 otherwise, MALE is an indicator variable representing the driver's sex, CURVED is a variable indicating whether or not the crash occurred on a curved or straight road segment, RURAL is a variable indicating whether or not the crash occurred in a rural or urban area, and VEH-AGE represents the age of the crash-involved vehicle.

Each of these models was run with a stepwise procedure that retained only ABS and those variables that were statistically significant. The final model results yielded estimates of the ABS coefficients (and their standard errors) for each database (FARS and the various state files), crash type, ABS system type, road surface type (favorable or unfavorable), for PCs and for LTVs. Since each coefficient represents the change in the log odds ratio of an ABS-relevant crash to an ABS-nonrelevant crash in the presence of an ABS-equipped vehicle, a negative coefficient indicates a reduction in crashes associated with the presence of ABS.

While crash reporting thresholds may differ somewhat from state to state, it appears reasonable to assume the effects of ABS should not differ dramatically. The results from the final models appeared to support this assumption. Therefore, the ABS coefficients for each state were statistically combined to form single estimates of the common log odds ratio for similar levels of ABS system type, crash type and road surface type, using the statistical methods described in Fleiss. These coefficients were translated into the percentage change in the expected number of relevant crashes using:

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\*RURAL was not recorded in the Missouri data. A variable indicating whether or not the crash occurred on a road with a 55 MPH or greater speed limit was substituted.

\*\*For LTVs, a variable VAN, indicating if the vehicle was a van was also included in the model.

$$\text{Expected percentage change} = 100 * [\exp(\text{ABS coefficient}) - 1] \quad (2.)$$

Replacing the (ABS coefficient) in the above equation with (ABS coefficient  $\pm$  1.96\*(standard error of the ABS coefficient)) yields estimates of the 95% confidence limits for the expected percentage change in relevant crashes. Tables 1., 2., and 3. present a summary of the statistically significant (at the  $p = 0.05$  level) effects of ABS for PCs, AWAL LTVs, and RWAL LTVs, respectively. In each Table, the crash types Roll = rollover crashes, Side = Side impact crashes with parked vehicles or fixed objects, Front = Frontal impact crashes with another motor vehicle in transport, Ror = Run-off-road frontal impact crashes with parked vehicles or fixed objects and Ped = Pedestrian crashes; crash severity All = All severities and Fatal = fatal crashes only. For each table, 95% CL represents the 95% confidence limit values for the percentage change shown.

**Table 1.**  
**Summary of Statistically Significant Effects of ABS**  
**for Passenger Cars**

Crash Severity	Crash Type	Road Type	% Change	95% CL
All	Roll	Fav	-17	-25 to -8
All	Ror	Fav	-13	-17 to -9
All	Side	Fav	+7	+1 to +14
All	Front	Unfav	-42	-45 to -39
All	Front	Fav	-18	-20 to -16
All	Ped	Unfav	-30	-35 to -24
All	Ped	Fav	-10	-14 to -7
Fatal	Roll	Fav	+51	+12 to +104
Fatal	Side	Unfav	+69	+5 to +174
Fatal	Side	Fav	+61	+19 to +117
Fatal	Front	Unfav	-40	-59 to -13
Fatal	Ped	Unfav	-38	-60 to -4

**Table 2.**  
**Summary of Statistically Significant Effects of ABS**  
**for AWAL-equipped Light Trucks and Vans**

Crash Severity	Crash Type	Road Type	% Change	95% CL
All	Roll	Fav	-40	-54 to -40
All	Roll	Unfav	-43	-60 to -20
All	Ror	Unfav	-33	-47 to -17
All	Ror	Fav	-24	-35 to -12
All	Side	Unfav	-35	-54 to -8
All	Front	Unfav	-38	-46 to -29
All	Front	Fav	-14	-20 to -8
Fatal	Roll	Fav	+97	+34 to +190
Fatal	Roll	Unfav	+125	+10 to +358
Fatal	Side	Fav	+111	+17 to +281

**Table 3.**  
**Summary of Statistically Significant Effects of ABS**  
**for RWAL-equipped Light Trucks and Vans**

Crash Severity	Crash Type	Road Type	% Change	95% CL
All	Roll	Unfav	-39	-48 to -28
All	Roll	Fav	-42	-48 to -34
All	Ror	Fav	-10	-17 to -3
All	Side	Unfav	-30	-40 to -18
All	Side	Fav	-13	-22 to -2
All	Front	Unfav	-10	-16 to -4
Fatal	Roll	Unfav	+89	+3 to +246
Fatal	Ror	Fav	-28	-44 to -7



## CONCLUSIONS

The findings for passenger cars in fatal crashes for this study are very similar to the earlier results. For passenger cars in non-fatal crashes the benefits in avoiding frontal crashes remain about the same. Side impacts and run-off-road crashes on unfavorable surfaces, went from a predicted increase in the earlier study to non-significance in these findings. In addition, there are decreases predicted for crashes involving pedestrians.

For light trucks and vans, the two types of ABS, i.e., AWAL and RWAL, were analyzed separately. No significant predicted changes in fatal crashes had been found for AWAL systems in the earlier study, while the current analysis shows some predicted increases in rollovers and side impacts (both crash types associated with loss of control). In non-fatal crashes with AWAL, frontals on good surfaces went from an increase to a decrease and run-off-road crashes went from non-significance to a decrease. For LTVs with RWAL, the most dramatic change is that both fatal and nonfatal frontal crashes on favorable and unfavorable road conditions no longer show an increase as was the case in the earlier study.

These results surely raise as many questions as they answer. The overall impact of ABS for total crashes and fatalities, i.e., across all crash types, was not estimated in this study. Meanwhile, it has been hypothesized that the apparent increase in loss of control type crashes, i.e., rollovers and side impact crashes, results from successful deliberate attempts to steer off the road in order to avoid worse targets (most notably, perhaps, pedestrians) that now become possible because the wheels do not lock up. Some of the improved predictions for ABS, especially regarding non-fatal crashes in which the driver may be under less pressure, could possibly be due to increased skill on the part of motorists in using ABS. Also, the systems themselves may have been improved. Further analysis is planned which will take into account, where possible, the generation of the ABS and the driver's amount of experience with ABS. Meanwhile, NHTSA urges drivers to gain an in-depth understanding of the operation of their ABS-equipped vehicles to utilize the safety potential of ABS.

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## EUROPEAN ACCIDENT CAUSATION SURVEY (EACS) METHODOLOGY

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### ABSTRACT

The emphasis of accident research is in general placed in the field of passive safety, so that consideration is devoted to measures, which reduce the consequences of an accident. Persuaded that accident avoidance is also needed to save more crash victims than new progress in passive safety, the **European Automobile Manufacturers Association (ACEA)** has taken the initiative in launching a "European Accident Causation Survey" with the support of the **European Commission** and under the aegis of the **European Road Safety Federation (ERSF)**.

Thus, five partners from European countries (Germany, Italy, Finland, France) have been collaborating since March 1996 and are building up a data bank on the causes of accident based on a scientific in-depth investigation of the pre-crash phase.

Although retrospective data collection will also feature in the work, it is thought that a "prospective study" based on a common questionnaire, prepared by these accident investigation experts, will provide more complete data about human, road, environment and traffic factors responsible for causing accidents.

It is only through such a scientific accident investigation of the pre-crash phase, combining detailed technical aspects and driver behavior data that it can be understood how and why accidents happen, and the effectiveness of solutions can be assessed in conjunction with full scale experiments and simulations.

This paper will describe the harmonized approach and methodology followed in this study to secure a reliable quantitative and qualitative understanding of the different phases of the crash.

prevention of accidents is therefore a major stake in this field. It clearly appears today that passive safety has limits and that other complementary means will have to be implemented to continue to reduce the number of road fatalities and casualties.

In the early 70's, teams were created in Europe [: **University of Birmingham** (United Kingdom), **ICE\***-**University of Loughborough** (United Kingdom), **ARU-Medical University Hannover** (Germany), **VALT\*\*** (Finland), **INRETS\*\*\*** (France), **LAB\*\*\*\*** (France)] to investigate the consequences of road crashes by in-depth case-by-case analysis involving engineers and medical doctors, or even psychologists. In fact, in-depth road accident investigations give a more detailed knowledge about different factors on the course of events behind accidents and their consequences than can be obtained from records based on forms from police, hospital or insurance one's.

These teams are still at work following the evolution and the progress for new generations of cars and working to solve new priority problems regarding long-term disability, the vulnerable population such as older car occupants and children, or structural compatibility between vehicles.

It is impossible to prevent every injury in a large number of accidents, and for complete freedom from injury, crash avoidance systems would also have to be completely successful. The existing technological possibilities for crash avoidance have to be selected and better defined taking into account the true needs of the drivers involved in pre-crash situations.

### INTRODUCTION

Many authorities in Europe refuse to accept the current toll of road accidents and request that improvements are made in the field of road safety. The

- \* ICE : Institute for Consumer Ergonomics.
- \*\* VALT : Finnish Motor Insurers' Centre - Traffic Safety Committee of Insurance Companies.
- \*\*\* INRETS : National Institute for Research on Transports and Road Safety.
- \*\*\*\* LAB : Laboratory of Accidentology and Biomechanic, PSA Peugeot Citroën - RENAULT.

Sufficient information on the causes of accidents is still lacking, although it is well known that more than 90 % are related to human errors<sup>1</sup>. It is only through a scientific accident investigation of the Pre-crash phase, combining detailed technical aspects and driver behaviour data that it can be understood how and why accidents happen, and that more effective solutions can be developed in conjunction with full scale experiments and simulation. Although retrospective data collection feature also in this work, it is thought that the "prospective study" based on a common questionnaire provide more complete data about the responsibility for causing accidents of human, road and environmental factors as well as traffic conditions.

So, after a retrospective pilot study based on one hundred German automobile accident reports conducted by DEKRA experts in 1993-1994, **European Automobile Manufacturers Association (ACEA)** decided to support a "*European Accident Causation Survey*" (EACS) with the following objectives :

- several countries involved ;
- focus on the pre-crash phase ;
- prospective study, so that most of the parameters to be collected are previously defined ;
- accident investigations, starting on the scene very soon after the accident, to increase the chance of collecting traces on the road, true final position of the cars, better description of the environmental conditions and driver interviews ;
- enlarged sample of accidents ;
- in-depth analysis of the interaction between vehicle, driver and road environment aspects according to this system safety approach :

		SUB-SYSTEM		
		Drivers	Vehicles	Infrastructures
S I T U A T I O N S	Pre-conflict - Design/Training - Wear/Life	Psychological Sensorial Cognitive Motor	Ergonomic Dynamic Interactions	Geometry Grip Signing Visibility Equipment
	Conflict	Perception Processing Action	Space-time Interactions	Dynamic

- use of a common questionnaire to allow a common data base ;
- accidents studied will reflect the statistical distribution of cases observed in each particular country ;

- experienced European investigation teams currently at work and able to carry out accurate accident reconstructions.

It was expected that a sample of at least two thousand fully documented pre-crash accident cases will be available before the beginning of the new millennium. This will allow the acquisition of a technical understanding of pre-crash processes, determination of typical accident scenarios and analysis of countermeasure efficiencies for an enhanced car safety contribution within a traffic system.

## KICK-OFF HISTORY

Over a period of about three years, **ACEA** contacted several institutions and universities in Finland, France, Germany, Italy, and United Kingdom who have a recognised expertise in accident investigation field. All expressed their interest in an active participation in such an important common research project. But some possible partners did not succeed in gathering all the necessary means and agreements to realise their aims.

So, on the initiative of the **ACEA**, under the aegis of the **European Road Safety Federation (ERSF)**, five accidentological partners :

- the **University of OULU**  
in co-operation with **VALT** (Finland),
- **INRETS** (France),
- **CEESAR** (France),
- **DEKRA** (Germany),
- **ELASIS** (Italy),

started working on the project "*European Accident Causation Survey*" (EACS) for the development of a European data bank on accident causation. It was defined as a First phase (from March 1996 until December 1997).

**ACEA** entrusted **CEESAR** to co-ordinate the work of the different partners.

This project constitutes the first European Accident Causation Data Bank. Moreover, beside this main focus on the causation, data related to the mechanisms of the accident (pre-crash steps) will be collected.

The project is supported by the **European Commission** ( part of EC Contract n°B3-B96-B27020-SIN2806 ) to collect, through co-ordinated efforts and on the basis of a common and harmonised methodology, more accurate information on the causes of traffic accidents in Europe.

A sixth team joined the EACS partners in April 1997 : **Accident Research Unit - Medical University Hannover** (Germany) for just 10 accident cases to be collected.

## EACS ORGANISATION

### General

**CEESAR** was entrusted by **ACEA** to co-ordinate the work provided by EACS partners. **CEESAR** was responsible for the collection of these data from its partners and organised the exchange of relevant information that was needed.

Every quarter, **CEESAR** presented a status report of the work carried out to the Pilot of the **ACEA-EACS Task Force**.

**CEESAR** arranged and chaired meetings, especially :

- a one-week workshop in March 1996 with the teams of experts at the EACS-Phase I kick-off,
- a one-day meeting (June 18<sup>th</sup> 1997) with teams representatives, Task Force members, and **European Commission DG VII** representatives.

The persons who assumed scientific responsibility for this study are :

- for **CEESAR** : Mr B.CHENISBEST
- for **ACEA** : Dr. C.TARRIERE till June 1997, Dr. J-Y.LE COZ after this date, as pilot of the **EACS Task Force**.

### EACS Partners

#### UNIVERSITY OF OULU / VALT

The investigation of road accident factors by teams of specialists from several fields started in Finland in 1968. The team members included traffic police officers and vehicle and road engineers. This operation provided new ideas and in-depth information for road safety work.

The operation is conducted and financed by the Traffic Safety Committee of Insurance Companies (**VALT**), a committee for safer road traffic in the Finnish Motor Insurers' Bureau. The other bodies involved in the activity are government departments and they contribute to cover costs by permitting their respective representatives in the teams to participate in the investigation work as if it were a part of their normal duties.

At present, there are a total of 13 investigation teams, one in each province and one in the city of

Helsinki. The original members are included, supplemented by physicians, psychologists, and experts in railway traffic. Generally, the members are government officials or experts. The total number of team members is nearly 200.

**University of OULU** is one of the 13 investigation teams. At the beginning of 1996, Mr. Lasse HANTULA <sup>2</sup>, **VALT** Secretary General Road Safety Director, designated it to **ACEA** as an **EACS** project partner.

Professor Timo ERNVALL is the project manager. In the Department of Civil Engineering, he is the head of the Traffic Engineering and Transports Laboratory. He was assisted in this project by Mr. Jani HUTTULA, senior researcher.

The investigation area covers the city of Oulu and the district approach 50 kilometres southwards, 50 kilometres northwards and 50 kilometres eastwards from Oulu. Mr. Kari PURANEN, Mobile Police Chief superintendent, Northern Finland Department, conducts the investigation group. It consists of :

- 2 police inspectors ;
- 2 medical members (: 1 orthopaedic surgeon, 1 psychiatrist) ;
- 3 vehicle inspectors ;
- 5 road technical members : Professor Timo ERNVALL, 3 research engineers, 1 laboratory technician.

Every month, in their investigation group, they discuss the collected accident files and their problems. They continuously improve their methodology. Mr. Pekka SULANDER made the reconstructions in **VALT** office in Helsinki.

**INRETS** means "Institut National de Recherche et d'Etudes sur les Transports et leur Sécurité". It is the French public research institute devoted to road transport.

Present in-depth accident studies form a part of the national "Vehicles and Safety on the Road (**VSR**)" <sup>3</sup> programme, they are aimed at improving knowledge of traffic accident causation. This programme, started in 1993, is carried out in close collaboration by **INRETS** and car manufacturers (**PSA Peugeot Citroën - RENAULT**).

Their work was to build up an in-depth accident database to :

- examine in-depth researches both in pre-crash and crash safety fields ;
- determine dysfunctions in the driver-vehicle-environment system ;
- identify specific countermeasures ;
- follow up and evaluate the various measures.

On EACS project, just worked for **INRETS** the "Accident Mechanisms" department located in Salon-de-Provence (south-east of France) - on responsibility of Mr. Francis FERRANDEZ<sup>4</sup> -.

Mr Yves GIRARD is the project manager ; he was helped on this project by Mr. Christophe PERRIN, researcher. The investigation area covers the rescue services' intervention area of Salon-de-Provence, which represents 15 kilometres around this city. The investigation team consists of three experts :

- 1 specialist who investigates on vehicle and road infrastructure ;
- 1 psychologist ;
- 1 researcher who collects medical informations.

A mechanics engineer helps them for reconstruction.

**CEESAR** stands for "Centre Européen d'Etudes de Sécurité et d'Analyses des Risques" (in English : "European Centre for Safety Studies and Risk Analysis"). It's a non-profit making association, bringing together automobile manufacturers, component manufacturers, technical universities, insurance companies, and individual acknowledged French medical and technical specialists.

Its aims are :

- establish relationship and information exchanges between its members in order to identify the role played by the human and technologic parameters in the traffic accidents and to estimate their economic impact.
- to promote researches, tests, surveys able to reduce the risk of accidents in collaboration with all concerned partners : research laboratories, medical people or universities, industry (particularly cars) insurance companies, teaching profession ...
- to develop education methods in order to put in place specialists able to overcome the synthesis between socio-economics and accidentology.

Mr Bernard CHENISBEST is the project manager. For collecting accident data, two groups of three persons each are acting jointly. The investigation area covers :

- for the first group, the city of Evreux and the district approach 16 kilometres southwards, 25 kilometres westwards, 7 kilometres northwards and 7 kilometres eastwards from Evreux.
- for the second, the city of Amiens and the district approach 15 to 20 kilometres around Amiens.

Each investigation group consists of :

- 1 vehicle expert, he also collects medical informations ;

- 1 psychologist ;
- 1 road infrastructure and reconstruction expert.

Moreover :

- for reconstruction studies, 1 researcher works with them ;
- for accident involving trucks or buses, two experts can join these groups.

**DEKRA AG** is an organisation of experts offering reports and analyses throughout Germany, with some 6000 employees including roughly 3200 engineers.

One of the activities of **DEKRA** is the compilation of technical expert reports in the motor vehicle field. Traffic accident reports focus on the reconstruction of road traffic accidents and the technical investigation of vehicles involved with regard to technical defects responsible for causing accidents.

Furthermore, expert reports serve to illustrate the central themes of the experts' activities which, for example, are of particular interest for training courses and regular technical test programmes.

Mr. Walter NIEWÖHNER is the project manager ; he was assisted on this project by Mr. Frank SCHMIDTS, engineer. The investigation area covers all Germany. About one hundred experts worked on this project by collecting informations. A copy of all written reports is sent to **DEKRA** headquarters, Accident Research department, in Stuttgart, where they were checked, codified and added to the EACS database.

**Accident Research Unit - Medical University of Hannover (ARU-MHH)** joined the EACS partners in April 1997.

Mr. Dietmar OTTE is the project manager. The investigation area extends from the urban to the rural regions of Hannover with a radius of approximately 60 kilometres. Engineers, medical experts, project assistants and students from the department undertake case investigations.

**ELASIS** is a consortium of companies of the **FIAT** Group, which was established in October 1988 with the aim of creating a scientific and technical "network" located in the south of Italy to support product innovation in the **FIAT** plants.

Since 1994, one department copes with investigations oriented towards a scientific and objective understanding of the accidents. At the beginning, **ELASIS** received a training in France by the **LAB-CEESAR** and exchanged information with **INRETS**.

Mr Vito CARRARA is the project manager. The investigation area is an approximately circular with a radius of about 30 kilometres and the operational headquarters in Pomigliano d'Arco (near Naples) is at the centre.

The investigation team consists of ten people :

- 3 vehicle experts ;
- 2 road infrastructure experts ;
- 2 reconstruction expert ;
- 2 doctors (2<sup>nd</sup> Medical University of Naples) to collect the medical information ;
- 1 psychologist to characterise the driver behaviour.

On the site of the accident, at least two experts are present.

## DATA COLLECTION

### Accident study - Statistical Distribution

The sample of accidents will include accidents with injuries involving at least one car (light vehicle < 3.5t ). The distribution of accidents per type will have to be as close as possible to the statistical pattern of accidents found for each country (types of road, types of vehicle, types of driver).

However, because drivers must be able to explain the precise circumstances of their accidents by interviews, it will be necessary to give priority to cases without serious brain injuries.

### Number of Accident cases Collected and Coded

Organisation (Country)	Number of cases	
	to collect Initially (March 1996)	and to code Finally (December 1997)
University of OULU / VALT (Finland)	85	43
INRETS (France)	85	85
CEESAR (France)	30	40
DEKRA (Germany)	700	720
ARU.MUH (Germany)	0	10
ELASIS (Italy)	100	115
<b>TOTAL</b>	<b>1000</b>	<b>1013</b>

The accident collection finally breaks down as follows :

- Single car accident : 196
- Car(s)-to-Car(s) \* : 405
- Car(s)-to-Truck(s)/Bus(es) \* : 89
- Car(s)-to-Two-wheeler(s) \* : 162
- Car(s)-to-Pedestrian(s) \* : 157
- Others : 4

\* These vehicles had or not a trailer.

## Mathematical Reconstruction

In the Reconstruction domain, when it's possible, the main objective was to obtain a quantification of the pre-crash phase in terms of vehicle kinematics and driver behaviours. For a quantitative and qualitative understanding of the different phases of the crash, experts filled a pre-collision table <sup>5</sup>, where interpretation that the driver has on the situation (Safety State, Risk State or Danger State) as well as the (possible) reaction (braking, swerving, etc.,...) are linked to time,

Vehicle kinematics are based on data collected on the site, like traces, skidmarks, collision point on the road and post-crash position of vehicles. An evaluation of the energy dissipated into vehicle deformations (so called "Equivalent Energy Speed") is estimated by experts.

Several computer programmes of accident reconstruction were used by the different teams involved. However, basic physic laws are of course the same.

## QUESTIONNAIRE

### Setting-up

A first (English version) questionnaire has been drafted on October 1994 by CEESAR on the basis of questionnaires used by DEKRA (ACEA Pilot study), ARU - MHH, VALT and LAB-CEESAR/INRETS.

On February-March 1996, high level discussions took place between European partners and CEESAR and ACEA members. Then, CEESAR has reviewed the questionnaire's structure, improved it, and suggested to EACS partners the specific codification.

For the homogeneity of the work between the five teams, answers of each question and their codification have been discussed during a one-week seminar organised by CEESAR in Paris (end of March 1996), and agreed by experts.

On August 1996, CEESAR organised an opinion pool : it sent a list of new possible improving changes, and required from all project's partners their agreement. Changes have been taken into account when all five partners' majority agreed.

The EACS questionnaire codification last update is thus September 3<sup>rd</sup> 1996.

## Questionnaire Hierarchy

The common questionnaire is composed of several parts which -if there is need to do so- can be used once or more. It consists of six main parts some of them divided in optional sub-parts (see Table 1) and of two additional one's which are only indirectly related to the accident causation :

- Secondary safety parameters (included in the other forms),
- Witness information (used to complete the available information).

**Table 1.**  
**EACS questionnaire Chapters**

Main Part	Optional Sub-Part	Number of questions
Accident Generalities	-	45
Road Infrastructure	-	92
Vehicle	For the whole vehicle	12
	For motor vehicles, except two-wheelers.	77
	For Cars and Light Trucks	57
	For Trucks and Buses	108
	For Trailers	103
	For Two-wheelers	23
Vehicle Occupant	For each occupant (including the driver or the rider)	33
	For the driver or the rider only	103
Pedestrian	-	85
Reconstruction	For the accident	3
	For each vehicle	68
	Pre-Collision Table	12
TOTAL		821

One accident may involve several Roads, Vehicles, Vehicle Occupants and/or Pedestrians. So it is necessary to fill in several forms of the same kind.

Specific rules have been established. Thus, normally, for an accident case, experts need to complete :

- one Accident General Form per accident,
- one Road Infrastructure Form per vehicle,
- one Vehicle Form per vehicle type involved,
- one Vehicle Occupant Form per occupant in concerned vehicle,
- one Pedestrian Form per pedestrian,
- one Reconstruction Form per vehicle.

A complete listing of the different subjects per chapter is included in the appendix.

### How does it work ?

For example, if we consider a car-to-truck (with trailer) accident - two persons are in the car -, accident investigators must fill :

EACS Forms		For the Car	For the Truck + Trailer
Accident Generalities	-	1	1
Road Infrastructure	-	1	1
Vehicle	For the whole vehicle	1	1
	For motor vehicles, except two-wheelers.	1	1
	For Cars and Light Trucks	1	0
	For Trucks and Buses	0	1
	For Trailers	0	1
Vehicle Occupant	For each occupant (including the driver or the rider)	2	1
	For the driver or the rider only	1	1
Reconstruction	For the accident	1	1
	For each vehicle	1	1
	Pre-Collision Table	1	1

that means to put answers for about 1215 items.

## MANUAL FOR CODING

During the study, a complementary document was written : it's the **Manual for coding the EACS's questionnaire**, which describes in detail how to use the questionnaire, the different definitions or arrangements to be used, how information should be interpreted into the coded format.

Contrary to the EACS's common questionnaire, its editorial content changed, according to the questions asked to **CEESAR** by its partners. Answers are provided by **CEESAR** after taking into account and having all teams' agreement.

This manual contains in addition articles or references to documents allowing thus a better and common understanding to themes and variables used in this project.

## DATABASE

The **EACS** database was structured like the questionnaire to obtain the most effective data processing : each form represents one table. The data bank system (DBS) was selected at **CEESAR** workshop (end March 1996). The way the data have to be filed in the DBS and communicated to the parties involved in the project met the requirements of the expert teams and **ACEA**.

To ensure the easy handling of data input, **CEESAR** developed, and distributed to its partners and **ACEA**, a data capture software tool, where input masks are oriented to the structure of the **EACS's** associated

questionnaire forms. Moreover, in each input masks, to display background information, for each EACS's variable (or question), a label is used for the coded answer.

CEESAR took care the DBS could be run with the number of data which is expected to be collected from 2000 accidents cases, and with sufficient computational time.

## EXCHANGES

During the two-years program, following a fixed timetable, CEESAR collected the computerised data from its partners, adding new data and any modifications to the EACS data bank.

CEESAR organised the coding process and especially the complete storage to share the EACS database to ACEA members. All collected results have been made available to ACEA in the format of the selected DBS and in ASCII format.

At the end of Phase I, possible copying of accident files can be asked to EACS partners by ACEA members.

CEESAR checked that information was coded according to the common care of specifications to ensure that a same understanding of the common procedure is reached. Every quarter, CEESAR presented to the Pilot of the Task Force EACS a status of the work carried out.

## CONCLUSION

- EACS - Phase I (1996-1997) can be considered as a success. Objectives are decently reached.
- The first sample of 1 000 accident cases will show the potential of this Survey. Nevertheless, to be useful to manufacturers and road safety, it is essential to increase the databank's size till at least 2000 cases.
- We could also think in the future - with a sufficient budget - to make available, with the EACS data bank, computer files of :
  - pictures of the road infrastructures and vehicle damages ;
  - a comprehensive sketch of the accident scene facts i.e. pre-crash, crash and post-crash areas (including road measurements, obstacles,

skidmarks, impact location, final position of vehicles) ;

- a sketch of the reconstruction, giving vehicles paths and locations, at each pre-crash phase.

## ACKNOWLEDGEMENTS

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## **Appendix 1 : EACS QUESTIONNAIRE SUBJECTS.**

### **Accident General Form**

Location.  
Date and Time.  
Weather conditions.  
Common Infrastructure description :Junction.  
Accident Type.  
Accident Severity.  
Prometheus.

### **Road Infrastructure Form**

Road type.  
Road restrictions.  
Road geometry.  
Road surface.  
Road equipment.  
Traffic.  
Difference between the approaching zone and the accident zone.

### **Vehicle Form - Part I**

Accident severity.  
General information.

### **Vehicle Form - Part II**

General information (Technical and administrative).  
Design specifications (Performance, technical design, driving aids).  
General technical state.  
Load during the trip.  
Defects (Braking, steering, suspensions,lights).  
State at the time of the accident.

### **Vehicle Form - Part III**

General information.  
Defects on tyres and wheels.  
Load during the trip.

### **Vehicle Form - Part IV**

General information.  
Defects on tyres and wheels.  
Load during the trip.

### **Vehicle Form - Part V**

General information.  
Design specifications.  
General technical state.  
Load during the trip.  
Defects on tyres and wheels.

### **Vehicle Form - Part VI**

Technical information.  
Defects.

### **Vehicle Occupant Form - Part I**

Personal status.  
4-wheeler vehicle occupant report.  
Child restraint data complement.  
2-wheeler occupant conspicuity and passive protection.  
Injury report.

### **Vehicle Occupant Form - Part II**

Personal status.  
Driving experience.  
Intoxication level.  
Trip in progress.  
Accident and emergency situations.

### **Pedestrian Form**

Personal status.  
Past accidents.  
Intoxication level.  
Pedestrian conspicuity.  
Trip in progress.  
Accident and emergency situations.  
Collision.  
Injury report.

### **Reconstruction Form - Part I**

General information.

### **Reconstruction Form - Part II**

Vehicle parameters.  
Aspects recorded at accident site.  
Pre-crash phases (vehicle behaviour, key events).  
Pre-collision table.  
Impacts and vehicle (Running-in impact speed, type of impact, EES, ...)  
CDC/TDC codification.  
Accident causation.

# A SURVEY OF CANADIAN DRIVERS' KNOWLEDGE ABOUT AND EXPERIENCE WITH ANTI-LOCK BRAKES

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## ABSTRACT

This study presents the results of an analysis of two sources of data: a sample containing 1392 drivers of ABS-equipped vehicles, and a dataset containing 405 ABS-related complaints. Survey respondents were asked about the purpose of ABS, the correct use of ABS, and whether their ABS had either prevented a collision or caused them to have one in the past two years. The complaints data were examined to determine to what extent the reported problems arose as a result of driver mis-use and/or mis-understanding of ABS.

About 18 percent of the ABS-users surveyed thought that pumping the brakes was the correct way to operate them, while close to 40 percent thought that the purpose of ABS was to stop faster, and/or prevent all skids. About 47 of the ABS-related complaints involved loss of control/extended stopping distance incidents with normally-operating ABS; about 73 percent of these incidents had resulted in collisions.

## INTRODUCTION

The potential of ABS to reduce collisions by improving driver control has been well-documented in controlled testing environments. However, the results of the collision-based research on the effectiveness of anti-lock brakes made possible by the widespread fitment of ABS in the early 1990s have demonstrated both positive and negative effects of ABS.

On the positive side, antilock brakes have been associated with significant reductions in multiple vehicle collisions, on both good and bad road surfaces. On good road surfaces, ABS has been associated with a nine percent reduction in multivehicle frontals (Hertz et al., 1995); a six percent reduction in side impacts (Evans and Gerrish, 1996); and reductions of 22 percent in crashes fatal to non-ABS road users, and 20 percent in multiple-vehicle crashes fatal to occupants of the other motor vehicle (Farmer et al., 1996).

Decreases have also been observed for bad road surfaces, i.e., wet/snowy/icy pavement; these reductions have been estimated variously at 13 percent (Evans, 1995), 28 percent (Kahane, 1994), and 35 percent (Hertz et al., 1995). Reductions for fatal multivehicle collisions

only have been estimated at 24 percent (Kahane, 1994), and 35 percent (Hertz et al., 1995), and for fatal pedestrian involvements at 27 percent (Kahane, 1994) and 34 percent (Evans, 1995).

The research has consistently shown that the clearest effect of ABS is for striking front-to-rear collisions on wet/snowy/icy surfaces; Kullgren (1994) has observed that the ABS vehicle is seldom the striking vehicle in a rear-end collision, and both studies which calculated the effect in terms of percent reductions estimated them at 32 percent (Evans, 1995), and 39 percent (Kahane, 1994).

Conversely, while ABS reduces the risk of crashing into a lead vehicle, it appears to increase the risk of being struck in the rear (Kullgren, 1994; Kahane, 1994; Evans and Gerrish, 1996); for example, Kahane (1994), observed a 27 percent increase in "struck in the rear" collisions for ABS-fitted vehicles, while Evans and Gerrish (1996) calculated an increased risk of being struck in the rear of about  $(30 \pm 14)\%$  for these cars.

The research has also consistently shown ABS to be associated with statistically significant increases in single vehicle collisions of various types on dry and wet surfaces (Kullgren, 1994; Kahane, 1994; Evans, 1995; Hertz et al., 1995; Farmer et al., 1996). Kahane observed a 29 percent increase in fatal single vehicle collisions on dry roads, and increases in every type of non-fatal single-vehicle collision studied, ranging from 15 percent for frontal impacts with fixed objects to 49 percent for rollovers, and 19 percent for all single-vehicle collisions combined; the increases in non-fatal single vehicle collisions were significant on both dry pavement (up 17 percent) and wet pavement (up 24 percent). Evans (1995) noted a 44% increase in rollover risk, while the second NHTSA evaluation (Hertz et al.) found that ABS was associated with increases in non-fatal single collisions on good and bad road surfaces combined, including a 24 percent increase in rollovers, a 15 percent increase in run-off-road collisions with parked vehicles or fixed objects, and a 36 percent increase in side impacts. Hertz et al. also found that ABS was associated with increases of 60 percent for fatal rollovers, and 91 percent for fatal side impacts with fixed objects. Most recently, for ABS-fitted GM mid-size cars, Farmer et al. noted a 17 percent overrepresentation in all fatal single-

vehicle collisions and disproportionate representations of ABS vehicles in collisions fatal to ABS vehicle occupants of 39 percent (all single-vehicle crashes), 47 percent (single-vehicle running off road); 37 percent (rollover crashes); and 29 percent (single-vehicle rollovers).

Given this mix of positive and negative effects, it is not surprising that attempts to demonstrate an overall benefit of ABS have resulted in failure to detect a net benefit (Highway Loss Data Institute, 1994) or the detection of only a very small net benefit of 3 percent (Evans, 1995).

It is fairly easy to explain the benefits associated with ABS in terms of the stopping tests, i.e., significant reductions in multivehicle collisions were found for collisions involving hard braking on slippery surfaces. However, explanations for the negative effects are both more difficult to explain and necessarily speculative in the absence of causal data.

The most easily understood negative effect of ABS is the increased likelihood of being rear-ended in an ABS-fitted vehicle. The most likely explanation of this finding is that the superior braking ability of a lead vehicle will logically put it at a higher risk of being hit by a following vehicle not fitted with ABS. However, it seems reasonable to suggest that this negative effect will disappear as more and more vehicles are equipped with antilock brakes.

The increase in single-vehicle collisions for ABS-equipped vehicles, however, is neither consistent with the stopping tests, nor as easily interpreted. One possibility is that it is a negative consequence of the very advantage that ABS provides, i.e., the ability to steer in an emergency situation. It is entirely possible that a certain proportion of rear-enders are simply being converted to single-vehicle collisions: the driver of an ABS car in an emergency situation may steer off the road rather than rear-end the lead vehicle, but in doing so, increases the risk of rollover or collision with a fixed object. The use of steering/avoidance maneuvers may also explain the increase in oncoming collisions detected by Kullgren (1994), if driving off the roadway is not an option and the driver attempts an avoidance maneuver that takes the vehicle even briefly into the opposing lane. Furthermore, given that ABS cannot be expected to reduce stopping distance appreciably on dry pavement (Kahane, 1994), the negative effect may be particularly evident on this type of road surface.

The most difficult negative effect to explain, however, is the significant increase in single vehicle collisions on wet/slippery pavement, given that ABS is designed to shorten stopping distance on these surfaces. This finding perhaps offers the strongest evidence for an explanation in terms of driver behaviour. Research on

behavioral adaptation has suggested that drivers may react to ABS technology by maintaining higher speeds, performing more dangerous maneuvers, accelerating more quickly, etc. (Grant and Smiley, 1993). Others have suggested that drivers of ABS cars may be using the brakes incorrectly, by either relieving pressure on the brake pedal or pumping the brakes (Williams and Wells, 1994). This study focuses on drivers' knowledge about, and understanding of, ABS in an attempt to provide some insight into the negative benefits associated with ABS.

## METHOD

Two sources of data were used: a public perception survey, and a database consisting of ABS complaints, and investigations.

The public perception data were generated in 1997 when Transport Canada contracted COMPAS Inc. to undertake a telephone survey on the driving public's perception of road safety in Canada. The research objectives were to position drivers' road safety concerns in the context of other modes of transportation, identify road safety issues of importance to them, evaluate their knowledge of road safety issues and discern their priorities for safety intervention.

Following a series of focus-group and telephone pre-tests, the survey was administered nationally between November 28 and December 15, 1997. The sample frame provided for a minimum of one hundred interviews per province and fifty per territory. To ensure sufficient representation in each region, smaller jurisdictions were oversampled, and the final data weighted to ensure that the results were representative of the national driving population. To ensure randomization within a household, the "next birthday" method of respondent selection was employed. The final sample consisted of 2,286 respondents, all of whom were at least 16 years of age and had driven a motor vehicle within the past twelve months.

The survey consisted of one hundred and two questions, a small subset of which were specifically related to anti-lock brakes. All respondents, whether they reported driving an ABS vehicle or not, were asked what the purpose of ABS is, i.e., stop faster, steer while braking, prevent all skids or other. Multiple responses were allowed, thereby enabling a clear picture of the sample in terms of their understanding of ABS, i.e., complete (those who gave only one response, and it was the correct one), partial (those who gave at least one incorrect response along with the correct one); and no understanding (those who gave only an incorrect response or responses).

The respondents who reported having driven a vehicle fitted with ABS were asked the remaining questions:

- how they would use ABS on wet or icy pavement (apply steady pressure; pump the pedal; other);
- whether their anti-locks had helped them avoid a collision in the last twenty-four months; and
- whether their anti-locks had caused a collision or near-collision in the last twenty-four months.

Those who thought that their ABS had helped them avoid a collision were asked two further questions: what they had almost collided with (another vehicle, fixed object, pedestrian, etc.); and how they had avoided the collision (e.g., braked and steered around the obstacle, braked and drove off roadway, etc.).

Those who thought that their anti-lock brakes had caused or nearly caused them to have a collision were asked two follow-up questions: the type of incident (collision/near-collision with another vehicle, fixed object, pedestrian, etc.); and whether the incident had occurred on-road or off-road.

The second data base consists of all ABS-related complaints made to Road Safety's defects investigation division since the mid-1970s (N=405). Information on the vehicle type, make and model year; collision or near-collision details; complainants' perceptions of the brake-related problem and the investigators' assessments were extracted, coded and entered into an electronic data base. Although these data cannot be assumed to be representative of all ABS drivers, or even all dissatisfied ABS drivers, these data can provide interesting and valuable information on experience with, and understanding of, anti-lock braking systems among a particular subset of drivers who use ABS.

The main thrust of the present analysis, then, is to describe ABS drivers' knowledge, understanding and use of, ABS, and to some extent, their positive and negative experiences with ABS. Given that the data available to the present study are nominally or ordinally scaled, differences were tested using the chi-squared test of significance.

## RESULTS

Sixty-one percent of the 2286 survey participants reported having driven an ABS-fitted vehicle (N=1392), and consisted of 832 men (59.8 percent) and 560 women (40.2 percent).

**Knowledge About ABS** - Respondents were asked whether the purpose of ABS was to enable the driver to steer while braking hard, to stop faster, to prevent all skids, or had some other purpose; multiple

responses were allowed. Although ABS will decrease stopping distance on wet pavement, it will increase it on others, e.g., snow, slush or gravel. Likewise, although ABS will prevent braking-related skids, it will not prevent skidding caused by traveling too quickly on slippery, i.e., icy or snowy, pavement. Since the main purpose of ABS is to enable steering while braking hard, this was defined as the "correct" response.

Interestingly, less than half (44.1 percent) of the drivers stated that the only purpose of anti-lock brakes was to enable them to steer while braking hard. A further 16.1 percent gave at least one incorrect response (stop faster and/or prevent all skids) with the correct one, while a notable 39.8 percent omitted "steer while braking" entirely and gave only one or more incorrect responses.

**Operation of ABS** - The second measure of drivers' understanding of ABS was the question about the correct method of applying ABS while traveling on an icy/slippery surface. Although 78.2 percent of them gave the correct response (apply steady pressure), 18.1 percent reported incorrect usage, i.e., pumping the brakes, while a further 3.7 percent didn't know.

Not surprisingly, there was a strong association between these two measures of ABS understanding. Those with full or partial knowledge about the purpose of anti-lock brakes, i.e., included "steer while braking" among their answers to the previous question, were much more likely to respond that the correct method of using ABS is to apply steady pressure ( $\chi^2 = 33.08$ , d.f. = 2,  $p < .00000$ ). Although neither variable was related to age, an effect of gender was detected for both. Men ( $n=832$ ) were more likely to report correctly both the purpose of ABS ( $\chi^2 = 29.58$ , d.f.=2,  $p < .00000$ ) and the method of use ( $\chi^2 = 26.21$ , d.f.=1,  $p < .00000$ ) than were women ( $n=560$ ).

**Collision Frequency** - The public perception survey contained a question on the frequency of collisions that was asked of all survey respondents, i.e., it was not part of the subset of questions specifically for ABS drivers, and asked only how many collisions the respondent had had in the past two years. In the absence of data on the collision type (single-vehicle versus multiple-vehicle) or severity, it has limited analytical value. Nevertheless, it does provide a basic measure of collision involvement for the ABS drivers, as a complement to the later questions on collisions the drivers considered to be related to ABS in some way.

The number of (non-ABS-related) collisions in the past two years was not found to be related to either kilometers traveled in the last year ( $\chi^2 = 3.678$ , n.s.) or sex ( $\chi^2 = .003$ , n.s.). However, a strong association between collision involvement and age was detected, and it was in the expected direction, with younger drivers

(16-39 years of age) much more likely to report a collision than drivers 40 years of age or older ( $\chi^2 = 19.04230$ ,  $p < .00001$ ). Furthermore, the age association held for both males ( $n=829$ ,  $\chi^2 = 14.855$ ,  $p < .0001$ ) and females ( $n=556$ ,  $\chi^2 = 4.767$ ,  $p < .05$ ). Number of collisions was not found to be associated with either knowledge about the purpose of ABS ( $\chi^2 = .315$ , n.s.), or correct usage of ABS ( $\chi^2 = .026$ , n.s.) for all ABS drivers combined. However, given the relationship demonstrated previously between sex and both ABS knowledge and usage, separate analyses were run for women and men.

It was found that female drivers younger than 40 years of age with no knowledge of the purpose of ABS were more likely to report at least one collision than were women with at least partial understanding of ABS ( $N=275$ ,  $\chi^2 = 4.845$ ,  $d.f.=1$ ,  $p < .05$ ). No relationship between ABS knowledge and number of collisions was found for men ( $N=831$ ,  $\chi^2 = 2.386$ , n.s.), or between ABS use (steady pressure versus pumping) and number of collisions for either sex.

**ABS-related collisions** - All ABS drivers were asked whether they believed that their anti-lock brakes had helped them avoid a collision in the previous two years, and conversely whether they thought the brakes had caused them to have a collision in the same time period.

A total of 370 respondents (26.6 percent) reported that their ABS had enabled them to avoid a collision. Of these, 73.8 percent reported that they had avoided colliding with another vehicle, 12.4 percent had avoided a collision with a fixed object, 2.9 percent had avoided a collision with either a pedestrian (2.4 percent) or a cyclist (.5 percent) and 3.8 percent had avoided hitting an animal.

Conversely, 6.6 percent ( $n=92$ ) of the 1392 ABS users reported that their anti-locks had caused them to have at least one collision or near-collision in the past two years. About 37 percent of the incidents involved another motor vehicle (29 collisions, and 5 near-collisions), with 17 percent of drivers ( $n=16$ ) reporting either a fixed object/off road collision ( $n=14$ ) or near-collision ( $n=2$ ). An additional 34 percent reported incidents in which they experienced extended stopping distance, i.e., went through an intersection, red light or stop sign. Overall, 95.7 percent of these drivers reported the incident to have occurred on the roadway, with only 4.3 percent reporting that the incident occurred off-road.

Interestingly, knowledge about the purpose of ABS was not associated with the purported contribution of ABS to either collision avoidance ( $\chi^2 = .632$ , n.s.) or causation ( $\chi^2 = 1.197$ , n.s.). Similarly, no association was found between ABS usage (steady pressure versus pumping) and either collisions purportedly avoided due

to ABS ( $\chi^2 = 2.07$ , n.s.), or caused by ABS ( $\chi^2 = 1.142$ , n.s.).

Among those who reported that ABS had helped them avoid a collision, 37.3 percent stated that they did so by braking and steering around the obstacle, while 5.7 percent reported braking and steering off the roadway without further incident. However, 47.6 percent ( $n=176$ ) reported that they avoided the collision by braking and stopping in time; in the absence of data on the pavement conditions, it is not possible to determine whether their ABS provided them with better stopping capability than conventional brakes would have.

The complaints data are remarkably similar in distribution of incident type and location to those surveyed who reported an ABS-related incident. As such, they should provide some insight into the ABS-related incidents reported by the 92 survey respondents.

First, and notably, is the fact that about 50 percent of the incidents that were attributed to ABS by the complainants turned out to be ABS malfunction or failure; about 30 percent of these involved Transport Canada recalls or major investigations, 12 percent were isolated ABS failures, and the remainder involved miscellaneous problems such as wheel speed sensor malfunctions and leaking ABS controllers. A further three percent of incidents were attributable to other vehicle problems (1.2 percent) or undeterminable (2.5 percent).

However, in 47 percent of the incidents reported to the investigations division, the drivers were reporting ABS failure or malfunction when the brakes were functioning normally. Overwhelmingly, these were loss of control incidents: the driver had experienced extended stopping distance, i.e., unwillingly run a red light or stop sign. Moreover, a considerable 81.6 percent of these cases occurred in weather/road conditions that were less than ideal, e.g., snow and/or slush.

Interestingly, the distribution of incident type among the ABS complaints is nearly identical to the survey respondents who reported a collision or near-collision due to ABS. Of the 405 complaints received, 40.2 percent involved a specific incident, e.g., a collision or near-collision, versus only 6.6 percent of the ABS drivers surveyed. However, of these, about 39 percent involved a collision or near-collision with another motor vehicle (versus 37 percent of those surveyed who reported incidents), 21 percent involved hitting or nearly hitting a fixed object or the ditch (versus 17 percent), and 36 percent (versus 34 percent) reported a loss of control incident, such as skidding or sliding through an intersection. About 95 percent of the complainants (compared with 96 percent of the survey respondents who reported an ABS-related incident) reported that the incident occurred on the roadway, rather than off the

road. Although caution should be exercised when generalizing from the complaints data to the survey data, it seems reasonable to surmise that a comparable percentage of the incidents attributed to ABS by these drivers were actually due to lack of knowledge about the longer stopping distance required by ABS on certain road surfaces, given the similarity of the distributions of incident type in both data sets.

## CONCLUSION

The association of ABS with increases in various collision types, especially single-vehicle run-off road crashes, found everywhere in the evaluation literature has raised questions regarding drivers' knowledge about, (mis)use and (mis)understanding of anti-lock brakes. The present paper represents a preliminary step in the exploration of the human factor that may underlying the negative benefits associated with ABS.

The survey data are, first of all consistent with the research that demonstrates the potential of ABS to reduce collisions. About 27 percent of the survey respondents reported that ABS had enabled them to avoid a collision, whereas only seven percent reported that ABS had caused them to have a collision or near-collision. Furthermore, a considerable 74 percent of those who identified a positive benefit reported that it was a collision with another motor vehicle that had been averted. Nevertheless, only 37 percent of them reported that they had avoided the collision by braking and steering around the obstacle, i.e., used ABS in the way it is intended to be used, while six percent reported that they had braked and steered off the roadway to avoid the crash. While those respondents had reported doing so without further incident, it is noteworthy that 17 percent of the respondents who reported a negative benefit of ABS had experienced a collision or near-collision by steering off the roadway, with another 34 percent reporting a loss of control incident, i.e., running a red light or stop sign.

The study also demonstrated a level of misunderstanding about anti-lock brakes that is consistent with findings reported elsewhere (Williams and Wells, 1994): close to 40 percent of the survey respondents failed to identify the ability to steer while braking as a purpose, main or otherwise, of anti-lock brakes, while about 20 percent thought that pumping the brakes was the correct method of using ABS. Additionally, women were less likely than men to state the correct purpose of ABS or to state the correct method of use. The need for public education, and its potential to reduce collisions, is further supported by the observation that women under 40 years of age with the least

understanding of ABS (i.e., who omitted "steer while braking" from the list of purposes of ABS) were more likely to report at least one collision than were women who demonstrated at least partial understanding of ABS.

Equally revealing was the observation that nearly 50 percent of the complaints data involved drivers reporting problems with anti-lock brake systems that were functioning normally, i.e., providing braking capability that is actually inferior to conventional brakes on particular road surfaces, increasing stopping distance and resulting in loss of control incidents. Furthermore, these incidents resulted in collisions some 73 percent of the time, which is consistent not only with the increase in collisions on snowy and/or slushy road surfaces, but with the need for public education about the reduced stopping capability of ABS in these conditions.

## ACKNOWLEDGMENTS

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# QUANTIFYING HEAD-UP DISPLAY (HUD) PEDESTRIAN DETECTION BENEFITS FOR OLDER DRIVERS

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## ABSTRACT

The current research was aimed at quantifying the potential *head-up display (HUD)* pedestrian detection benefits for older drivers. In a parked vehicle on a closed-course, test participants were required in rapid succession to read a digital speedometer (positioned either head-up or head-down) and a distant speed limit sign. 24 drivers were tested ranging from 59 to 71 years old. Liquid-crystal glasses were used to limit the driver's view of the forward scene to the time period immediately surrounding display glances. In the second half of testing, subjects were told that during a few trials a pedestrian would appear. On these trials, subjects were to immediately press a button. During these pedestrian trials, results indicated a HUD detection time advantage and a trend toward fewer missed pedestrians with the HUD. Indeed, 7 of the 9 fastest mean pedestrian detection times across all 16 conditions tested occurred in HUD conditions. These results clearly suggest HUDs improve the driver's ability to see forward scene events (and hence, potentially traffic safety) surrounding display glances.

## INTRODUCTION

Since 1988, passenger car manufacturers have introduced automobiles which can present visual information to the driver through the windshield by way of a HUD (Weihrauch, Meloeny, and Goesch, 1989). The HUD allows the driver the ability to access visually displayed information in closer proximity to forward scene events relative to a conventional HD, instrument panel display. In this first generation of production HUD vehicles, *head-up (HU)* information has included digital speed, turn signals, high beam indicator, and master and/or specific telltale warnings. Figure 1 illustrates an "all segments on" image from a GM production HUD. Under most driving conditions only the speedometer is shown on the HUD, which is translucent and either blue- or yellow-green (depending on manufacturer). In addition, the HU information has been redundantly displayed at conventional *head-down (HD)* locations, and the driver has been able to dim the HUD off. A detailed description of the first HUD introduced by GM can be found in Weihrauch et al. (1989).

The next generation of HUDs may include information which would not be redundantly displayed at traditional HD locations, provided technological advances



Figure 1. Production HUD graphics.

can be made to ensure HUD image visibility under a range of conditions comparable to HD displays. These advances involve increasing image source luminance and/or HUD optical system efficiency. Assuming this technological challenge can be overcome, automotive HUDs have increased potential to improve the driver-vehicle interface, present information which could not be effectively communicated via a HD display, and increase display space and interface design flexibility. In addition, future HUDs may include more advanced driver content, including navigation/route guidance, intelligent cruise control/forward collision warning, and infrared night vision displays (Grant, Kiefer, Wierwille, and Beyerlein, 1995). These relatively unexplored content areas may be better suited for yielding the greatest potential benefit of a HUD to the driver.

The primary focus of this study was to address the claim that current *automotive HUDs improve the driver's ability to see forward scene events (e.g., a crossing pedestrian) during the time period immediately surrounding when they are accessing displayed information*. This claim is subsequently referred to as the *improved forward visibility claim*. A secondary focus of this study was to address the claim that current *automotive HUDs reduce driver's re-focusing times from the display to the outside world*, subsequently referred to as the *reduced focusing time claim*. This latter claim provides more indirect evidence of a potential HUD safety benefit. A more extensive review of these two claims, as well as other positive and negative HUD claims, are provided in Kiefer (1996a).

The current research was also a follow-up to the Kiefer and Gellatly (1996b) field study. In this earlier



study, subjects in a parked car were required in rapid succession to correctly read a speedometer and report forward scene targets under both expected and unexpected target conditions. Liquid-crystal glasses were used to limit the driver's view of the forward scene to the time period immediately surrounding display glances. Under the unexpected target conditions, drivers were not given any information as to what to expect with respect to these targets, but they did know when the target might occur. Under these conditions, results indicated a HUD advantage for a number of real-world targets, including standing and crossing pedestrians near parked vehicles, and approaching and crossing bicyclists.

It has been proposed that these results supporting the improved forward visibility claim can be interpreted in terms of a "*HUD benefit time window*" (Kiefer, in press). In order to clarify the time period during which the HUD is expected to support the improved forward visibility claim, consider a driver deciding to glance at his/her speedometer. Furthermore, consider the time-course of the ensuing speedometer eye movement with a HU versus HD digital speedometer. During this ensuing eye-movement, the HUD is expected to improve a driver's ability to see forward scene events (and hence, potentially traffic safety) during the time period which starts when the eyes would have arrived at the HD speedometer (i.e., the beginning of the HD speedometer fixation), and ends when the eyes would have returned to the roadway after fixating the HD speedometer. During this time period, defined as the *HUD benefit time window*, the driver's eyes are in closer proximity to forward scene events in the HU relative to HD speedometer condition (approximately 15° closer to the driver's visual horizon with the GM HUD design).

This time window is shown below in Figure 2 for data gathered in an in-traffic study along with the roadway-display transition time, display fixation time, and display-road transition time for the HD and HU digital

speedometer conditions (Kiefer, 1991; Kiefer, in press). For these data, the duration of the HUD benefit time window was 777 ms. This time window can be broken down into four different time periods,  $t_3$  through  $t_6$ , which are preceded by time periods  $t_1$  and  $t_2$  (shown in Figure 2).

During the first 71 ms ( $t_1$ ), the driver's eyes are transitioning from the roadway to the speedometer in both display conditions. During the next 32 ms ( $t_2$ ), the driver's eyes in the HD condition are completing a visual transition from the speedometer to the roadway, while the driver's eyes in the HU condition are fixating the speedometer. It is somewhat unclear whether the HUD benefit time window should include  $t_2$ , particularly the beginning of  $t_2$ . During this time, the driver's eyes in the HD condition may be transitioning just past the HU speedometer location, while the driver's eyes in the HU condition are just beginning to fixate and process the HU speedometer. Consequently, a more conservative estimate of the HUD benefit time window is assumed here which does not include any portion of  $t_2$ .

During the first 508 ms of the HUD benefit time window ( $t_3$ ), the driver is fixating a HU versus HD speedometer, which puts the driver's eyes approximately 15° closer to the driver's visual horizon. During the following 102 ms of this time window ( $t_4$ ), the driver's eyes in the HD condition are fixating the speedometer, while the driver's eyes in the HU condition are transitioning from the speedometer to the roadway. During the next 33 ms of this time window ( $t_5$ ), the driver's eyes in the HD condition are beginning a visual transition from the speedometer to the roadway, while the driver's eyes in the HU condition have nearly completed the corresponding visual transition. Finally, during the last 134 ms of the HUD benefit time window ( $t_6$ ), the driver's eyes in the HD condition are completing a visual transition from the speedometer to the roadway, while the driver's eyes in the HU condition are fixating on the roadway.

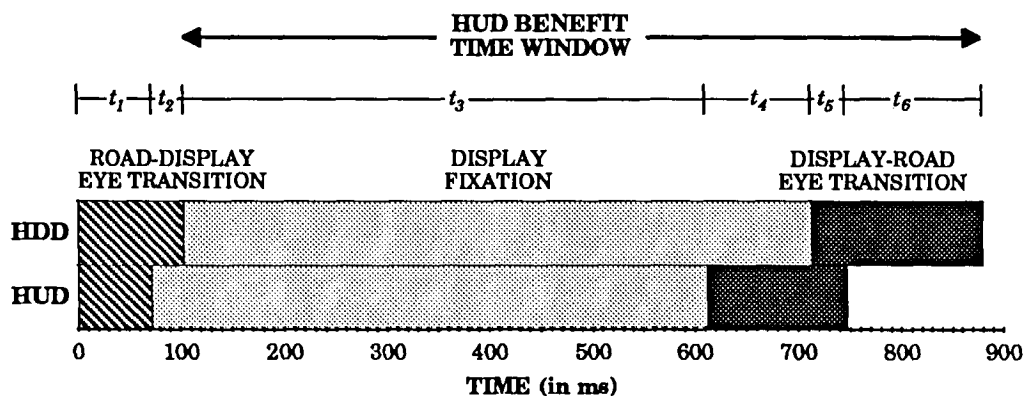


Figure 2. The HUD benefit time window and the roadway-display transition time, display fixation time, and display-road transition time for HD and HU digital speedometer conditions (from Kiefer, in press).

It should be stressed that  $t_6$ , which corresponds to the frequently cited HUD time savings for getting the driver's eyes back to the roadway, represents only 17% of the total time estimated for the HUD benefit time window. In contrast, 65% of the total time estimated for this time window corresponds to  $t_3$ , when the driver is fixating a HU versus HD speedometer.

In the current study, older drivers were asked to perform tasks with both a HU and HD digital speedometer in a parked vehicle on a closed test track. Liquid-crystal glasses were used to limit the driver's view of the forward scene. A speedometer and speed limit sign were modified to allow pre-selected values to be displayed. The first task involved reading a speedometer and then a distant speed limit sign in rapid succession. Results from this task were aimed at addressing the reduced focusing time claim, and were also used to set stimulus duration levels tailored for each subject during the second task. In the second task, drivers were again asked to perform the previous task; but they were told that during a few trials, a pedestrian would be positioned in the forward scene. On these pedestrian trials, subjects were instructed to immediately press a hand-held reaction time button as soon as they detected the pedestrian. The pedestrian targets were either at a 100 or 300 foot (30.5 or 91.4 m) distance, standing or crossing the road, and either near a parked vehicle or isolated. This second task was aimed at addressing both the improved forward visibility claim (with pedestrian detection performance) and the reduced focusing time claim.

There were several important differences between this study and the previous Kiefer and Gellatly (1996) study. First, this study was focused on testing older drivers, whereas the Kiefer and Gellatly study sampled a wider age range. Second, the methodology involving pedestrian targets was changed to allow gathering pedestrian detection times (Kiefer and Gellatly used percent correct performance measures), which allowed more precisely quantifying HUD benefits in terms of time and travel distance savings. Third, the probability of pedestrian target occurrence across trials was substantially lower in this study (13.5%) relative to the Kiefer and Gellatly study (80%). Fourth, stimulus durations were tailored individually for each subject (a constant duration was used across subjects in the Kiefer and Gellatly study) to increase sensitivity to detecting any performance differences across displays. Furthermore, in order to more closely mimic typical speedometer glance times (particularly for older drivers), substantially longer stimulus durations were used here (on average, about 700 ms) relative to the Kiefer and Gellatly study (250 ms). Fifth, in order to mimic real-world behavior as much as possible, subjects were instructed to stop performing the speedometer and sign reading tasks whenever a pedestrian

was detected (Kiefer and Gellatly required correct performance on each task).

## METHOD

All 13 male and 11 female test participants were licensed drivers and were tested to ensure they met the minimum standard of 20/40 far visual acuity. The subjects ranged between 59 and 71 years ( $M=65.2$  years), and were tested individually in one 90-minute session and paid \$75. None of the drivers had previously owned a HUD vehicle.

Data were collected on a straight, black asphalt test track which was closed to all other traffic during testing. The test vehicle remained parked in the center of the road throughout testing. All testing was conducted during daytime hours. Nearly all testing was conducted under dry weather and dry road conditions. During the few sessions when light rain was falling, the windshield was cleared prior to each trial.

The HU and HD digital speedometers of the test vehicle (a 1994 Buick Regal) were representative of current production speedometers, with one exception being that the latest production HUDs provide substantially higher maximum daytime luminance. The instrument panel cluster for the test vehicle was retrofitted with a 1993 Buick Regal digital instrument panel cluster. Subjects were instructed to set the HUD no brighter than necessary to clearly and comfortably see the speedometer. Overall, the mean HUD luminance setting was 887 cd/m<sup>2</sup>, and the mean HUD:background contrast ratio during testing was 1.9:1. The nominal digit height for the HU and HD digital speedometers was 0.6° and 1.7°, respectively. The HU speedometer was positioned at front bumper depth (2.3 m) and centerline to the driver. At the start of testing, the top of the HU speedometer was set for each driver at 4.6° below the driver's visual horizon. For several drivers, such a setting prevented viewing the entire speedometer. As a result, the average look-down angle across all drivers was 4.5°, and the top of the HUD superimposed the roadway at an average of 22.6 meters. The HD speedometer was located at approximately 18.5° below the driver's visual horizon. It should be noted that, in practice, HUD look-down angle settings vary somewhat across drivers, depending on the driver's eye position and preference. Drivers of GM vehicles equipped with HUDs are advised in the owner's manual to adjust the HUD as low as possible in their field of view while the entire HUD image remains fully visible (i.e., so the HUD appears just above the driver's front hood).

The brief amount of time drivers had available to view the visual stimuli was controlled via *PLATO spectacles* (acronym refers to *P*ortable *L*iquid-crystal

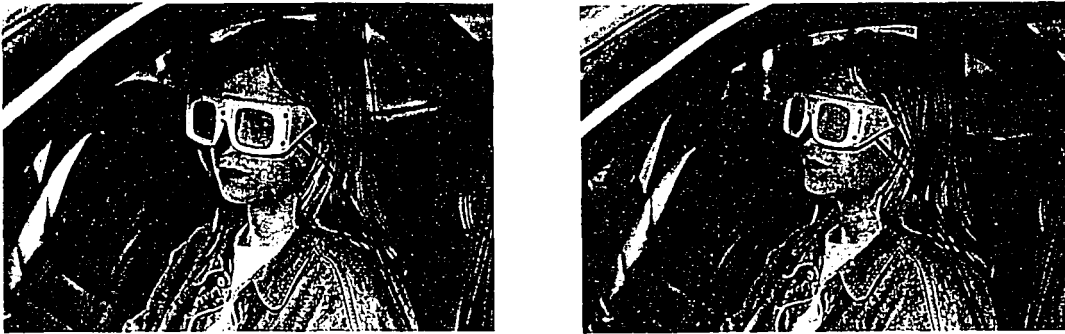


Figure 3. Open and closed states of "shutter type" liquid-crystal glasses.

Apparatus for Tachistoscropy via visual Occlusion) (Milgram, 1987). The open and closed states of these spectacles are illustrated in Figure 3. In the open state of these spectacles, the driver had a clear view.

After receiving the open signal, the spectacles needed 8 ms to reach a 20% light transmission and an additional 62 ms to reach the peak transmission of 72%. In the closed state, the driver viewed a whitish, uniform, milky texture; and vision was effectively occluded. After receiving a close signal, the spectacles needed 32 ms to reach a 20% light transmission and an additional 68 ms to reach a 0% light transmission. Given these on/off switching characteristics, it is important to stress that the stimulus duration values reported in this paper refer to the difference in time between the open and closed signals, rather than the duration in which any given minimum light transmission value was exceeded. To put this in perspective, a 700 ms stimulus duration corresponds to either a 630 ms, 724 ms, or 800 ms stimulus duration, depending on if one assumes a 72%, 20%, or 0% light transmission criterion, respectively.

In the first task, referred to as the *Speedo + Sign task*, drivers were asked in rapid succession to read the speedometer (values ranging between 50 and 69) and then a distant speed limit sign (reading either 55 or 65 miles-per-hour). A small, color video camera allowed the experimenter the opportunity to ensure the driver was performing the tasks in the correct sequence. Immediately before the spectacles were briefly opened, subjects were

given a 425 ms warning tone, followed by an 800 ms interval with no warning tone. This general trial sequence was used throughout the study, and is illustrated in Figure 4.

The speedometer and sign values were changed trial-to-trial by the back-seat experimenter and outside experimenter, respectively. The on-board and outside experimenters communicated via FM radios. An experimenter box positioned in the back seat allowed activation of one of the two speedometers and selection of the appropriate speedometer value. For the speed limit sign, a regulation rural road speed limit sign was created using Type II retroreflective Scotch-Lite material (The Michigan Department of State Highways, 1973). A 55 mile-per-hour (mph) and 65 mph speed limit sign were mounted back to back on a gray sleeve that fit over a post attached to a gray pedestal. The speed digits were 25.4 cm in height. The sign assembly was positioned 300 feet (or 91.4 m) in front of the vehicle, and 12 feet (or 3.7 m) from the right edge of the road.

For each display condition, a staircase threshold method (Cornsweet, 1962) was continued for 40 trials until a 50% identification threshold value (i.e., the stimulus duration at which drivers were able to read both the speedometer and sign with 50% accuracy) was obtained based on the last four reversals. For the first three trials, step changes of the stimulus duration were made in 200 ms increments, beginning at 1000 ms. Thereafter, step changes were made in 50 ms increments.

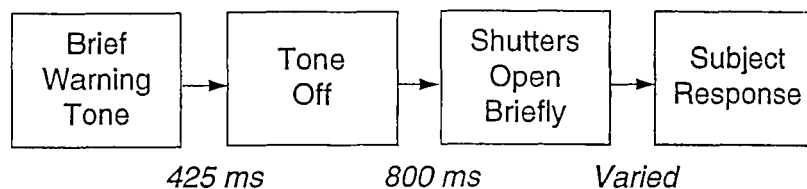


Figure 4. General trial sequence.

The back-seat experimenter recorded the driver's responses and set the appropriate stimulus duration values. The obtained 50% identification threshold value was the measure of driver performance analyzed. The within-subject variable analyzed for this task was display (HU and HD) and the between-subjects variable was display order. Display order was counterbalanced.

In the second task, referred to as the *Speedo + Sign/Pedestrian task*, drivers were again asked to perform the Speedo + Sign task, with two important differences. First, they were told that during a few trials a pedestrian would be positioned in the forward scene. On these trials, they were instructed to immediately stop performing the Speedo + Sign task and press a hand-held reaction time button as soon as they detected the pedestrian. Drivers were provided examples of each of the eight possible pedestrian target types (described below) prior to performing the task. Second, drivers were tested at two stimulus durations, calculated individually for each subject. The first stimulus duration was the higher of the two 50% identification threshold values found in the head-up versus head-down display condition in the previous Speedo + Sign task, referred to as the *maximum threshold (MT)*. The second stimulus duration added 200 ms to the MT value ( $MT + 200$ ). The rationale for tailoring stimulus durations was to attempt to create an equally demanding Speedo + Sign task for each driver, and to equally limit each driver's ability to focus attention on anticipating and detecting pedestrians. The stimulus duration, speedometer values, sign values, and pedestrian stimuli were varied on a trial-by-trial basis within each of the 4 blocks of trials. Four random block sequences were counterbalanced across display condition.

The forward scene consisted of a roadway with a white 1995 Chevrolet Sport van parked on the right side of the road just prior to the near (100 foot or 30.5 m) pedestrian target distance, and a blue 1995 Buick Skylark parked on the right side of the road just prior to the far (300 foot or 91.4 m) pedestrian target distance. The near and far "live" pedestrian targets wore matched denim shirts, denim jeans, and white canvas tennis shoes. The four pedestrian target types at both the near and far distance included a side-view of a pedestrian standing on the right side of the road, a side-view of a pedestrian crossing right to left on the right side of the road, a side-view of a pedestrian standing on the left side of the road, and a side-view of a pedestrian crossing left to right on the left side of the road. All pedestrian targets on the right side of the road occurred immediately to the left of and just forward of the parked vehicle. An illustration of the near and far right crossing pedestrian targets are shown in Figure 5. (Illustrations of the near and far right standing pedestrian target types can be found in Kiefer and Gellatly (1996b).) Each pedestrian target type was fully visible to the driver when the spectacles were in the open state.

The 100 and 300 foot (or alternatively 30.5 and 91.4 m) target distances employed were chosen to bound the upper and lower range of distances deemed critical in order for a driver to brake to a complete stop prior to reaching an obstacle in its path (assuming the driver would not have chosen or been able to avoid the obstacle by steering the vehicle). These distances were generated by combining a range of driver perception-reaction times (P-RTs), vehicle speeds, and vehicle braking distances at these speeds. In this case, driver P-RT refers to the time between when the forward obstacle first becomes visible to the driver and when the driver initiates a brake application (Olson and Sivak, 1986). The lower bound of the range of driver P-RT values considered, 0.7 sec, represents the mean value obtained under conditions in which an alerted driver encountered an obstacle in their driving lane after cresting a hill (Olson and Sivak, 1986). The upper bound of the range of driver P-RT values considered, 2.5 sec, was intended to be representative of a higher-percentile driver P-RT, and is based on design policy of the American Association of State Highway Transportation Officials (AASHTO) (Neuman, 1989). The range of speeds considered, 35-50 mph, account for the posted speed limits at the site of 57% of all non-occupant traffic fatalities (National Highway Traffic Safety Administration, 1986). The corresponding vehicle braking distances at these two speeds (67 and 144 feet, respectively) were again based on AASHTO design policy. The range of distances generated by combining the driver P-RT, speed, and braking distance variables varied from 103 feet (0.7 sec driver P-RT, 35 mph speed) to 328 feet (2.5 sec driver P-RT, 50 mph speed).

During each of 4 test blocks, subjects experienced 32 trials with no pedestrian present. Display condition was alternated between blocks, with half of the subjects experiencing the HD display condition first. During trial blocks 1, 2, 3, and 4, these 32 trials were interspersed with an additional 4, 6, 6, and 4 pedestrian trials, respectively. Overall, pedestrians occurred on 13.5% of all trials. Four of the 8 pedestrian targets were presented once during each of the four blocks, twice in each display condition. Each of these four targets occurred with 2.7% probability. These targets included the near right standing, near right crossing, far right standing, and far left crossing pedestrian targets, which were presented at the MT, MT, MT + 200, and MT + 200 durations, respectively. The remaining 4 of the 8 pedestrian targets were experienced exactly once by each subject (two targets in each display condition), and hence, these targets were examined separately with display as a between-subjects factor. Each of these four targets occurred with 0.7% probability. During block 2, the near left crossing and far left standing pedestrian targets were presented at the MT + 200 and MT durations, respectively. During block 3, the near left standing and far right crossing pedestrian targets were



Figure 5. Near and far right crossing pedestrian targets.

presented at the MT + 200 and MT durations, respectively. Overall, it should be noted that pedestrian targets occurred on the left side of the road (in isolation) and the right side of the road (near a parked vehicle) with 4.7% and 8.8% probability, respectively.

Two separate driver performance measures were analyzed for Speedo + Sign/Pedestrian task. The first measure analyzed was the percent of trials in which *both* the sign and the speedometer were correctly identified during trials in which a pedestrian *was not* presented. The within-subject variables analyzed for this measure were display (HU and HD), stimulus duration (MT, MT +200), and practice (first versus second half of testing). The second measure analyzed for this task was pedestrian detection times. For 4 of the pedestrian target types (near right standing, near right crossing, far right standing, and far left crossing), the within-subject variables analyzed for this measure were display (HU and HD) and pedestrian target type. For each of the remaining 4 pedestrian target types (near left crossing, far left standing, near left standing and far right crossing pedestrian) the between-subjects variable analyzed for this pedestrian detection time measure was display (HU and HD).

## RESULTS AND DISCUSSION

A factorial Analysis of Variance (ANOVA) was performed on each driver performance measure, and the criterion set for statistical significance was  $p < 0.05$ . Results for the first task drivers performed, the Speedo + Sign task, indicated no significant effects ( $p > 0.40$ ). For the second task, the Speedo + Sign/Pedestrian task, the average MT value employed across subjects was 734 ms. During trials in which no pedestrians were presented, results for the percent correct identification measure for the Speedo + Sign task indicated main effects of display ( $F(1, 23) = 13.66, p < 0.005$ ) and stimulus duration ( $F(1, 23) = 64.75, p < 0.0001$ ), and a Display x Stimulus Duration interaction ( $F(1, 23) = 6.55, p < 0.05$ ). Follow-up simple main effect tests indicated display had a significant effect on percent correct identification rates at both stimulus durations (MT, ( $F(1, 23) = 19.37, p < 0.0005$ ; MT + 200 ms, ( $F(1, 23) = 5.79, p < 0.05$ ). At the MT stimulus duration, the mean percent correct identification rates for the HU and HD display conditions were 63.2% and 49.4%, respectively. At the MT + 200 ms duration, the corresponding mean percent correct identification rates were 84.0% and 76.5%, respectively. Overall, this absolute level of task performance suggests this task was challenging enough to deter drivers from focusing their attention on detecting pedestrians.

Unlike results from the first task, the second task (which added a pedestrian detection component) showed support for the HUD reduced focusing time claim. This discrepancy in findings could have several explanations.

First, support for this claim may be contingent on practice with the HUD, which is consistent with earlier results (Kiefer and Gellatly, 1996b). Second, the technique used for measuring driver performance in the second task may have been more sensitive to detecting any differences across display conditions. Third, the driver's concern about the potential presence of a pedestrian target may have interfered more with speedometer and sign reading task performance in the HD relative HU condition.

Detection times and miss rates for each pedestrian target type are shown in Table 1. During trials in which pedestrians were presented in the Speedo + Sign/Pedestrian task, results indicated there was a trend toward higher pedestrian miss rates with the HD relative to HU speedometer. Overall, 21 of the 32 missed pedestrians occurred in the HD condition, and 4.4% and 2.3% of the pedestrian targets were missed in the HD and HU display conditions, respectively. These results also indicate that the relatively small differences in miss rates found for 5 of the 8 pedestrian target types all favor the HUD condition, suggesting a potential HUD advantage based on these limited data. In addition, a total of 12 and 8 false alarms occurred in the HD and HU display conditions, respectively. This suggests that the HUD pedestrian detection time benefits reported below are not due to subjects adapting a less stringent criterion for responding to a pedestrian target in the HU condition.

Results for the pedestrian detection time analysis in which pedestrian target type was treated as a within-subjects variable (near right standing, near right crossing, far right standing, and far left crossing pedestrian) indicated main effects of display ( $F(1, 23) = 30.83, p < 0.0001$ ) and pedestrian target type ( $F(3, 69) = 111.10, p < 0.0001$ ), and a Display x Pedestrian Target Type interaction ( $F(3, 69) = 7.84, p < 0.0001$ ). Follow-up simple main effect tests indicated a HUD pedestrian detection time advantage for 3 of the 4 pedestrian targets in this analysis. These included the near right standing ( $F(1, 23) = 27.59, p < 0.0001$ ), near right crossing ( $F(1, 23) = 10.20, p < 0.005$ ), and far left crossing ( $F(1, 23) = 18.38, p < 0.0005$ ) pedestrian target types. For the near right standing, near right crossing, and far left crossing pedestrian targets, the mean detection time advantage attributed to the HUD was 224, 87, and 281 ms, respectively. Results for the remaining 4 pedestrian target types in which display was a between-subjects variable (near left crossing, far left standing, near left standing and far right crossing pedestrian) indicated a HUD pedestrian detection time advantage for the near left standing pedestrian target type ( $F(1, 19) = 4.79, p < 0.05$ ), and a marginally significant advantage for the far right crossing pedestrian target type ( $F(1, 18) = 3.08, p < 0.10$ ). For the near left standing and far right crossing pedestrian targets, the mean detection time advantage attributed to the HUD was 302 and 325 ms, respectively. It is also worthwhile to

**Table 1.**  
**Mean Pedestrian Detection Times (in ms) and Number of Missed Pedestrians (indicated in parentheses)**  
**as a Function of Display, Pedestrian Distance, Lateral Location, and Movement**

PEDESTRIAN TARGET DISTANCE = 100 FEET (30.5 METERS)

	Left-Side (Isolated)		Right-Side (Near Van)	
SPEEDOMETER	Standing	Crossing	Standing	Crossing
Head-Down	1062 (3/12)	751 (1/12)	1069 (3/48)	740 (0/48)
Head-Up	760 (1/12)	708 (1/12)	845 (1/48)	653 (0/48)
HUD Time Savings	302 *	43	224 *	87 *

PEDESTRIAN TARGET DISTANCE = 300 FEET (91.4 METERS)

	Left-Side (Isolated)		Right-Side (Near Car)	
SPEEDOMETER	Standing	Crossing	Standing	Crossing
Head-Down	1248 (4/12)	1130 (2/48)	1303 (6/48)	1161 (2/12)
Head-Up	994 (1/12)	849 (1/48)	1300 (6/48)	836 (0/12)
HUD Time Savings	254	281*	3	325 **

Note. \*p < .05 (minimally). \*\*p < .10.

**Table 2.**  
**Rank Ordering of Mean Pedestrian Detection Times (in ms) as a Function of Display, Pedestrian**  
**Distance, Lateral Location, and Movement**

Pedestrian Target Type				
Display	Movement	Distance (in feet)	Lateral Location	Mean Detection Time (Miss Rate Percentage)
1. Head-up	Crossing	100	Right	653 (0%)
2. Head-up	Crossing	100	Left	708 (8.3%)
3. Head-down	Crossing	100	Right	740 (0%)
4. Head-down	Crossing	100	Left	751 (8.3%)
5. Head-up	Standing	100	Left	760 (8.3%)
6. Head-up	Crossing	300	Right	836 (0%)
7. Head-up	Standing	100	Right	845 (2.1%)
8. Head-up	Crossing	300	Left	849 (2.1%)
9. Head-up	Standing	300	Left	994 (8.3%)
10. Head-down	Standing	100	Left	1062 (25.0%)
11. Head-down	Standing	100	Right	1069 (6.3%)
12. Head-down	Crossing	300	Left	1130 (4.2%)
13. Head-down	Crossing	300	Right	1161 (16.7%)
14. Head-down	Standing	300	Left	1248 (33.3%)
15. Head-up	Standing	300	Right	1300 (12.5%)
16. Head-down	Standing	300	Right	1303 (12.5%)

note that for the far left standing pedestrian target, overall, 4 (of 12 possible) pedestrian targets were missed in the HD condition, whereas only 1 target was missed in the HU condition.

It is also interesting to note, that across all trials (i.e., without weighting pedestrian target type frequency), near pedestrian targets were detected on average 306 ms faster than far targets, crossing pedestrian targets were detected on average 260 ms faster than standing targets, and left-side (isolated) pedestrian targets were detected on average 303 ms faster than right-side targets (near parked vehicles). Similarly, across all trials, pedestrian miss rates for targets at the near and far distances were 4.2% and 9.2%, respectively. Pedestrian miss rates for standing and moving targets were 10.4% and 2.9%, respectively. Pedestrian miss rates for left- and right-side targets were 8.3% and 5.8%, respectively. In addition, miss rates were particularly high for left-side standing pedestrian targets in the HD condition. Averaging across both pedestrian distances, 29% of these pedestrian targets were missed. This pattern of results may be due to the reduced overall probability of targets on the left versus right side of the road (4.7% versus 8.8%), the lack of pedestrian movement cues, and/or that the speedometer and sign reading task oriented driver's attention to the right side of the road.

## CONCLUSIONS

Overall, these pedestrian detection results found with older drivers are consistent with and extend previous research supporting the improved forward visibility claim attributed to HUDs (Flannagan and Harrison; 1994; Kiefer and Gellatly, 1996b; Okabayashi, Sakata, Furukawa, and Hatada, 1990; Sakata, Okabayashi, Fukano, Hirose, and Ozone, 1987; Sojourner and Antin, 1990; Weihrauch et al., 1989). Furthermore, there was a HUD pedestrian detection time advantage ranging from 87-325 ms for 5 of the 8 pedestrian target types (near right standing, near right crossing, near left standing, far right crossing, and far left crossing). At 35 MPH, these HUD time savings range from 4.5-16.7 feet (or 1.4-5.1 m) travel distance. At 55 MPH, these HUD time savings range from 7.0-26.2 feet (or 2.1-8.0 m) travel distance. It should also be stressed that there was a trend toward fewer missed pedestrians with the HUD. Overall, 11 pedestrians were missed in the HUD condition, whereas 21 pedestrians were missed in the head-down condition.

Overall, this pattern of pedestrian detection time results favoring the HUD can also be seen in Table 2 which ranks all 8 pedestrian target type conditions for each display as a function of mean pedestrian detection time. These data indicate that 7 of the 9 lowest mean pedestrian detection times occurred in the HUD condition. More generally, it should also be noted that these results were found under conditions in which the HUD did not

superimpose the forward scene event, which is argued to be representative of the vast majority of driving (Kiefer and Gellatly, 1996b).

The failure to find a HUD advantage for the relatively inconspicuous far standing pedestrian targets may have been caused by the stimulus duration, since a HUD advantage for these targets was previously observed in a similar task with a shorter stimulus duration (250 ms) (Kiefer and Gellatly, 1996b). In addition, both the current study and Kiefer and Gellatly study found no difference in pedestrian detection performance across displays with the near left (isolated) crossing target, the most conspicuous pedestrian target.

A few points should be made with respect to the practical implications of the observed pedestrian detection results. First, even though these experimental conditions do not fully replicate a driver encountering an unexpected pedestrian, it should be stressed these HUD pedestrian detection time benefits occurred under conditions with relatively low pedestrian probability and high pedestrian location uncertainty (such that targets were somewhat unexpected when they did occur). Perhaps most importantly, these HUD pedestrian detection time benefits occurred for 3 of the 4 pedestrian targets (including both crossing pedestrian targets) near parked vehicles. Second, it should be noted that the pedestrian target distances employed (100 and 300 feet, or equivalently, 30.5 and 91.4 m) were chosen to bound the range of distances deemed relatively critical in order for a driver to brake to a complete stop prior to reaching an obstacle in its path (assuming the driver would not have chosen or been able to avoid the obstacle by steering the vehicle) These distances were generated by combining a range of driver P-RTs, vehicle speeds, and vehicle braking distances. Third, to the extent that accidents are caused by allocating visual attention to displays, these results suggest HUDs will improve traffic safety. Although accident data are generally not recorded or categorized in a manner which allows one to reliably estimate the number of such accidents, a keyword analysis of approximately 190,000 police report narratives from the 1989 North Carolina accident database suggested that for 0.82% of these accidents, driver vision was directed into the vehicle and this was the primary cause of the accident (Wierwille and Tijerina, 1993). Of this small portion of accidents, driver vision was directed into the vehicle at information which could be potentially shown on a HUD in about 13% of the cases. Unfortunately, police reports are not an entirely reliable source of accident causation, for a variety of reasons (e.g., driver/officer insensitivity to or misrepresentation of accident cause).

In conclusion, this research has come much closer than previous research toward the goal of understanding both the nature and magnitude of the real-world implications of the claimed eyes-on-road benefit of



HUDs. These results clearly suggest HUDs improve the older driver's ability to see forward scene events (and hence, potentially traffic safety) surrounding display glances. On a closing note, it should be stressed that the conclusions drawn in this paper cannot be readily generalized to other automotive HUDs which differ on fundamental HUD design parameters (e.g., HUD location).

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## HELPING OLDER DRIVERS BENEFIT FROM IN-VEHICLE TECHNOLOGIES

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### ABSTRACT

Age-related changes in cognitive, perceptual, and motor abilities are thought to be responsible for older driver safety problems and reduced mobility. In-vehicle navigation and collision avoidance technologies may help counter some of the performance limitations associated with aging. Whether or not older drivers will purchase and use such technologies to increase their safety and mobility depends on how well system designers understand the special needs and capabilities of this group and incorporate them into device designs. This paper will examine research findings related to older driver safety problems and capabilities that are relevant to the design of advanced technology, in-vehicle systems.

### INTRODUCTION

Developers of Intelligent Transportation Systems (ITS) are designing in-vehicle devices and services to improve driver safety and mobility. The products are generally grouped into two categories: collision avoidance systems and traffic information systems. Some of these products are expected to be of particular value to older drivers because of their perceived need for enhanced safety and mobility.

The future older driver market for such products may be huge. By 2000, the Census Bureau estimates that about 12.8 percent of the population will be over 65; by 2010, the percent rises to 13.3; and increases to 16.4 percent by 2020 as the "baby boomers" enter this age group. Currently, the American Automobile Manufacturers Association estimates that drivers 60 and older are the principal purchasers of 23 percent of new passenger cars in the United States. This percent is likely to increase over time along with the changing demographics.

Will these future seniors buy and benefit from such ITS devices? The answer depends on two issues: The extent to which the devices have functions and features that address the specific safety and mobility needs of seniors; and whether they are designed in accordance with human factors practices and

principles so that they minimize distraction and are easy to understand and operate. If these issues are not addressed, the technology may not only be a turnoff to older drivers, it may create new problems for them. This paper examines crash statistics, mobility patterns, in-vehicle technologies, and human factors research for insights relevant to these issues.

### SAFETY AND MOBILITY

Older drivers' safety problems have been documented extensively in terms of their performance capabilities, actual on-road behaviors, and crash statistics. Mobility problems have been described in terms of when and how much they drive.

Performance - The basic findings of the performance studies are that relative to younger drivers, older drivers experience more glare sensitivity, more restricted head/neck movement, and slower reaction time to events. Research has also shown that some older drivers have a narrowed field-of-view and increased difficulty noticing all the critical objects in their visual field. One measure of this problem is called "useful field of view." Research by Ball and Owsley has shown that older drivers who have a poor "useful field of view" are at increased risk of crashes. For many of these measures, the variability in performance from driver to driver is much greater for older drivers than younger drivers. This variability means that representative older drivers have to be considered when designing and evaluating in-vehicle equipment to minimize the possibility that the equipment is inadvertently designed for a biased segment of users, e.g., senior "super stars." Although some of these age-related changes in performance capabilities are often thought to adversely affect senior driver safety, their actual role depends on the ability of older drivers to adjust their driving behaviors to compensate for these changes as well as the extent to which vehicle and roadway designs are compatible with older driver capabilities.

Crash Characteristics - In terms of the overall number of crashes, younger drivers (under 25) are involved in four times

as many reported crashes as drivers older than 69. Adjusting the number of crashes to reflect the rate per licensed driver within each age group shows that involvement rates decrease as age increases. (Figure 1) To more accurately reflect the safety problem of older drivers, Eberhard (1998) has noted that these data need to be adjusted for the number of licensed drivers who actually drive, which tends to be lower for the oldest drivers. An indicator of a driver's exposure to risk of a collision while on the road is computed by dividing the number of crashes by the number of miles traveled. (Figure 2) These data (NHTSA, 1998) indicate that the highest crash rates per mile driven occur for drivers under 24 and for drivers over 75.

One interpretation of these statistics is that older drivers are involved in relatively few crashes because they do not drive many miles, but have a high risk of crashes when they do drive. However, this per mile adjustment assumes that each mile driven is equally hazardous for all age groups. This assumption may not hold because the urban roads most often used by older drivers are more congested and have more hazardous intersections than expressway miles more often traveled by the middle age drivers (Janke, 1991).

Older drivers' crash patterns can be describe in terms of the percent of their crashes having various characteristics. Many of their crash patterns are similar to those of younger drivers. One exception is crashes at night. Drivers between 65 and 74 have 12.5 percent of their crashes after dark compared to 33 percent for drivers 16-24. The primary reason for this difference is the fewer miles driven by older

drivers at night. Crashes occur most frequently at intersections for all age groups. However, drivers over 64 have a larger proportion of their crashes at intersections (60 percent) than other age groups (50 percent). At intersections, older drivers have increased problems when turning left. This problem may be related to the research findings that some older drivers have narrow fields-of-view and poor perception of spatially separated sources of information.

Compared to younger drivers, older drivers have only slightly larger percentages of their crashes involving lane changing and backing. Lane changing occurs in about 4.8 percent of crashes for drivers over 64 compared to 2.6 percent for drivers aged 25 - 64, and 2.7 percent for those under 25. Backing is involved in about 4 percent of crashes for drivers over 64 compared to about 2 percent for each of the younger age groups. (Derived from NHTSA 1996 General Estimate System)

However, it is important to keep these relative

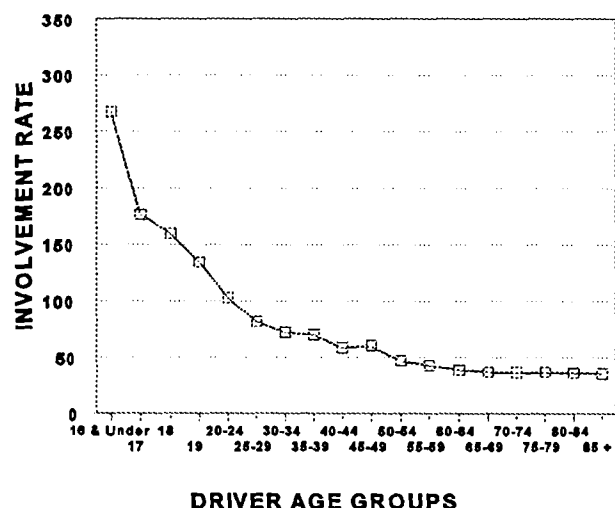


Figure 1. Crash Rate per 1000 Drivers, 1996.

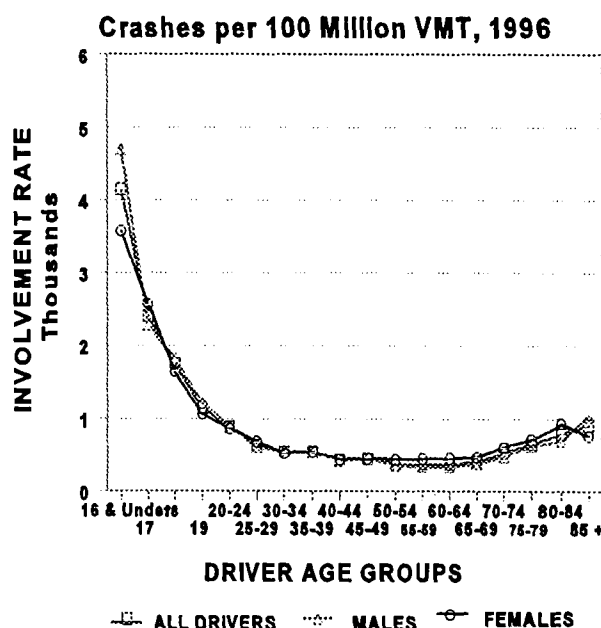
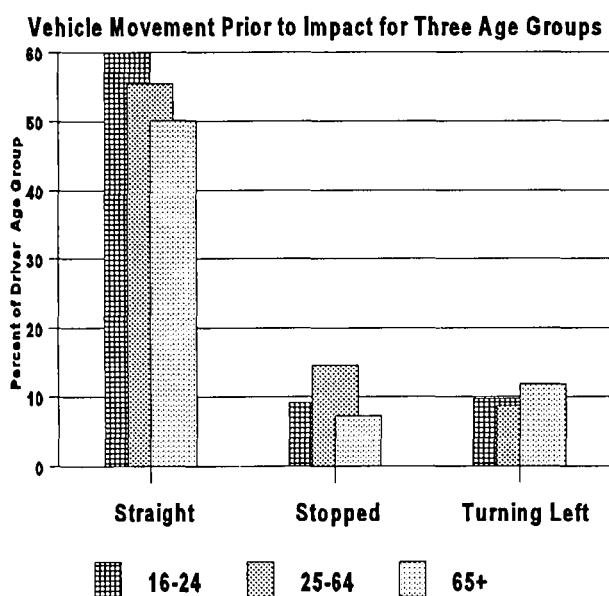


Figure 2. Crash Involvement Rate per Mile Traveled.

involvement percentages in perspective. As shown in Figure 3, the most frequent pre-crash maneuver involving older drivers is also the most frequent one found in all age groups: "going straight." The second most frequent maneuver is "stopped in traffic." Third is "turning left." These three categories account for about 75 percent of the vehicle movements prior to impact in the oldest age group. In part, these data reflect the frequency with which drivers make various maneuvers. That is, drivers are going straight much

more of the time than they are turning left. Although older drivers have a greater percent of their crashes when turning left compared to younger drivers, the difference is not large. Drivers going straight prior to a collision are often involved in rear-end crashes. Although older drivers are in the striking vehicle in a smaller percentage of such crashes than drivers between 16 and 24 years of age, their percent involvement is about the same as drivers between 25 and 64 years old. Specifically, drivers 65 and over are in the rear-end, striking vehicle in 13.6 percent of their crashes, compared to 17.9 percent for drivers between 16-24, and 13.4 percent for drivers between 25 and 64. (Derived from NHTSA 1996 General Estimate System)

**Driver Behaviors** - On-road behaviors are demonstrated to some degree by traffic violation characteristics. Studies have shown that compared to younger drivers, older drivers have proportionally more violations for failure to yield, failure to obey signs/signals, and improper turns. Conversely, they are under-involved in speeding and alcohol violations. (NHTSA, 1993)



**Figure 3.** Percent of drivers in different age groups going straight, stopping, or turning left prior to impact.

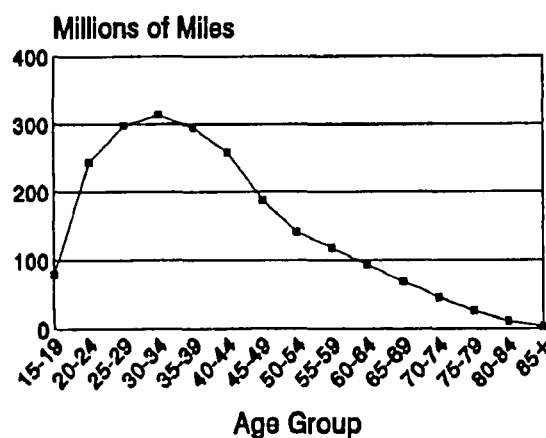
Source: NHTSA 1996 General Estimate System

**Mobility** - How can older drivers have reasonably good safety records compared to younger drivers despite all the noted psychological and physiological changes with age? One answer is found in the driving patterns of older drivers. Some older drivers may compensate for their changing capabilities by modifying when, where, and how they drive. They drive less frequently at night. They take an indirect route to avoid

making a left turn at an unsignalized intersection. They avoid highway driving. They drive slower. In the extreme, some older drivers cease driving. In other words, they seem to be adjusting their driving to reduce perceived risks. In terms of total miles driven, Figure 4 (NHTSA, 1993) shows the steady decline in mileage as age increases. More research is needed to determine how much of this decrease is due to concern over increased risk (e.g. inability to see well at night) versus other factors (e.g., less need to drive to places at night).

The above data suggest that one of the questions for future research is whether in-vehicle technologies that address older driver safety problems will give drivers more confidence to alter their driving habits and thus enhance their mobility, without jeopardizing their safety. For example, despite increased night vision problems, older drivers have few nighttime crashes. Would technology that helps older drivers see better at night, encourage them to take more night trips without increasing their crash rate per mile driven?

In terms of safety, older drivers may benefit from some of the same collision avoidance technologies as younger drivers, even though their crash patterns are somewhat different. Both groups have a need to prevent rear-end collisions with vehicles ahead, lane change crashes with vehicles to the sides, crashes with intersecting vehicles, and backing crashes.



**Figure 4.** Total Miles Traveled.

## IN-VEHICLE TECHNOLOGIES

From the user's point of view, several problems can affect the degree to which in-vehicle technologies will achieve their potential to enhance safety and mobility. These problems are associated with equipment design and operation which does not consider the human factors requirements of the driver. If the drivers' capabilities to understand and operate the devices are not compatible with device design, overall system effectiveness will be diminished. In addition to

reducing effectiveness, lack of consideration of driver capabilities may reduce safety. This problem may arise if these technologies are too complicated and distracting. For older drivers, such problems could make the technologies "bitter pills" which provide some benefits but also some adverse side effects. What is the right prescription for these technologies to enhance their benefits and minimize their side effects?

Head Up Displays - Head Up Displays (HUD) epitomize this "bitter pill" dilemma for older drivers. This technology may be a component of various in-vehicle products for displaying information such as route directions, collision warnings, traffic signs, enhanced forward vision, and vehicle status. By displaying information superimposed on the forward road scene, HUD may help reduce the driver's eyes-off-road time--a potential benefit to older drivers with limited field-of-view and difficulty attending to spatially separated sources of information. Also, because the HUD image is focused at a far enough distance that refocusing and reaccommodating to read the display is minimized, older drivers would not need to look through the near correction in their eyeglasses. On the other hand, researchers are concerned that HUD may have characteristics detrimental to older drivers. For example, if the display contains too much information, it could be distracting. If the display is too bright, too large, or located close to the line of sight, it could mask the presence of critical roadway objects.

The National Highway Traffic Safety Administration (NHTSA) is currently sponsoring research at The Scientex Corporation to investigate older driver reaction and performance using HUD compared to auditory displays and displays on the instrument panel. Three types of information were presented on each display type: collision warning, navigation, and vehicle speed information. The study approach used a fixed-based driving simulator to present filmed scenes containing critical roadway objects. Subjects were measured in terms of how accurately and quickly they responded to display information as well as roadway events in the filmed driving scene. Preliminary findings are suggesting that older drivers prefer vehicle gauge information to be displayed on a HUD. Auditory displays were preferred for most other information types by all age drivers. Surprisingly, younger drivers found the HUD more distracting than older drivers. One possible explanation is that the relatively poorer peripheral vision of older drivers allowed them to ignore the HUD display which was located below their direct line of sight. Further analyses will assess the extent to which their peripheral vision problems affect their ability to utilize the information displayed on the HUD. The study will also determine whether older drivers can devote more attention to the roadway if they can hear some navigation and warning information. The results will help assess the value of HUD to older drivers and define some of the design parameters that

may help them to use HUD more effectively.

To obtain further insight into potential HUD benefits and drawbacks, future research needs to focus on collecting real world, on-road baseline data describing the extent to which older drivers become distracted and divert their attention from the road scene. Such data would quantify how and when older drivers are distracted by current vehicle instrumentation and form the basis for comparison with behaviors when using HUD.

Collision Avoidance Systems - Collision avoidance systems detect potential collisions and use auditory, visual, or haptic (e.g., brake pulse) signals to warn drivers of the need to take avoidance maneuvers. These electronic systems may provide direct safety benefits from reduced crashes as well as indirect benefits because they may give older drivers the confidence to use safer, limited-access highways instead of secondary roads with intersections.

In order for such systems to be most effective, the design of the driver interface (i.e., the controls and displays) and operating characteristics need to be compatible with driver capabilities to process the warning information. Driver failures to comprehend the information, select an appropriate response, or perform the response can lead to an ineffective system. For example, a warning signal that cannot be heard or seen will not attract driver attention; several similar warning signals in a vehicle or non-standardized warnings in different vehicles can confuse drivers; if the false alarm rate of the warning is too high, drivers may not take appropriate action; if the urgency of the warning is not conveyed, drivers may not respond fast enough. Thus, effective warning system design requires knowledge about driver information processing capabilities and limitations.

In recognition of the importance of designing the interface of crash avoidance systems to be compatible with drivers' abilities and needs, NHTSA published preliminary human factors guidelines that recommend features and functional requirements to help assure that drivers understand and can respond quickly and appropriately to warning information. (Lerner, et. al. 1996) The guidelines included the following recommendations:

- 1) Use multiple levels of warning for any particular device. The "imminent crash warning" would use an intrusive signal; the "cautionary warning" would provide the driver with greater advanced warning without being disturbing.
- 2) Use warning signals that are standardized for uniqueness for "imminent crash warnings"
- 3) Because no warning modality will be completely effective under all conditions, "imminent crash warnings" should be presented in two modes (e.g., visual and auditory)

These guidelines were developed in part to help identify gaps in research where more data would be needed to refine

the recommendations. Such research is needed to determine auditory warning characteristics (e.g., loudness, uniqueness, time duration); visual display characteristics (e.g., location, brightness, symbology); and operational characteristics (e.g., false or nuisance alarms, response time, detection zone).

In the case of forward collision warning systems, there are numerous questions about the most effective display parameters for alerting the driver without making the system so annoying that drivers shut the system off. For example, what modality (visual, auditory, haptic) should the display use, what symbology best informs drivers, what threat detection criteria represent the best tradeoff between too many nuisance alarms and needed collision warnings?

One of the important characteristics that can affect the benefits of a forward collision warning system is driver response time to the warning. A system that does not provide its warning in time for drivers to perceive and respond will not be effective. While many studies have been conducted to measure perception/reaction times, they are not directly relevant to the design of in-vehicle warning systems. One relevant study of the response of drivers to emergency warnings in a vehicle was conducted by Vernet and Fraigneau. Drivers in a simulator had to brake in response to an auditory warning at unexpected times. The experimenters measured the time between the alarm and the time it took the subjects (N=114) to step on the brake pedal. The data indicated that 99 percent of the response times were under 1.36 seconds. The findings also indicated that when performing more complex tasks (e.g., conversing with a passenger while driving) older drivers had longer response times. Also, the variability of the response time increased with age. Thus, warning systems based on average times of younger drivers may not give older drivers enough time to respond to the signal and avoid the crash. However, to the extent that older drivers follow at longer distances and slower speeds than younger drivers, they may be able to compensate for their slower response times.

Another simulator study of braking response time as influenced by collision warnings was conducted by Vercruyssen, et. al. Subjects performed four tasks of varying complexity in a driving simulator. They were asked to brake as quickly as possible in response to a lead car braking and to auditory and visual collision warning systems. The task complexity was varied by having subjects respond when their car was stationary, when driving on an empty road, when following a car at a comfortable distance, and when following very closely. Without the warning signals, as task complexity increased, the older driver response time increased compared to that for younger drivers. However, with a warning, age differences were not significantly different. These findings suggest that forward collision warning systems may have the potential to help some older drivers compensate for their age-related slowing of response time. However, it is important to

find out the extent to which older drivers choose headways that correspond to the more difficult levels of task complexity found in this study. If they do not follow cars at distances as close as younger drivers, then warning system design parameters can be chosen accordingly.

Future studies to determine effective design parameters of the driver/vehicle interface for forward collision warning systems need to take into account other characteristics of older drivers. For example, should forward collision warning information be displayed on HUD? An argument against this HUD application is that a distracted driver might not notice the warning information quickly enough to respond to the threat. Given the relatively weaker peripheral vision of older drivers, designing an effective display may be particularly problematical. However, a bright, pulsating, and properly located display may be effective in attracting a driver's attention without being as annoying as an auditory display.

Human factors design issues for rear object detection systems are being evaluated in NHTSA-sponsored research.(Harpster, et. al.) This study is an example of how quantifying driver on-road behaviors, in this case when backing the vehicle, can be used for recommending the driver interface and operation of a warning system. Initial findings are indicating, for example, that older drivers are far more likely to use their mirrors than younger drivers when backing. The research also found that, surprisingly, older drivers, even with their slower reaction times, did not take significantly longer than younger drivers to stop in response to a warning alarm. The reason was that older drivers appeared to compensate by driving slower and keeping their foot on the brake while backing. These findings have implications for the timing of warnings and the location of visual displays.

Navigation Systems: Navigation system displays that are complicated and require visual attention while driving may increase safety problems for older drivers. Interestingly, it has even been shown that older drivers have a tendency to look at an information screen, whether or not information was actually displayed. (Pauzie, 1994). As noted above, displays that require close focusing will be more difficult for older drivers with presbyopia to see clearly. These problems suggest that navigation systems with auditory displays and carefully designed HUD or displays located at the top of the dashboard may be safer for older drivers. If visual information needs to be displayed, the size of the information can make a significant difference to older driver performance. For example, making the symbols or letters large enough can allow older drivers to process the information as efficiently as younger drivers. (Pauzie, 1994)

A properly human engineered navigation display can help minimize adverse safety effects for older drivers. Can the functions provided by such a system increase safety while enhancing mobility? Safety can be indirectly enhanced if the navigation information reduces the workload needed for

searching for unfamiliar roads and gives the driver needed time to be in the proper lane for turning. More research is needed to determine the extent of such benefits. Whether mobility will be enhanced to the extent that drivers will venture to new and unfamiliar places has been addressed in a study by Oxley et.al. 1994. They observed and questioned a sample of older drivers who were given navigation systems to use. About 40 percent of the older drivers said that they would drive to new and unfamiliar places if they had a route guidance system in their own vehicles.

Vision Enhancement Systems - One of the common complaints of older drivers is the difficulty of driving at night, due to headlight glare and the difficulty seeing very far with conventional headlighting systems. Two types of vision enhancement systems (VES) are being developed which may extend the driver's visibility range: a near-infrared system which uses an active IR light source to sense and display the scene ahead on a Head-Up Display superimposed along the driver's line of sight; and a far-infrared system which passively detects IR radiation from roadway objects and displays them at an angle below the line of sight. One of the key questions is whether older drivers will take advantage of VES capabilities to drive more at night. Current research is concentrating on the basic question of the extent to which VES improve seeing distance to critical objects and how VES design parameters influence this distance.

One study that evaluated how much a prototype near-infrared system could improve older driver visibility was reported by Ståhl, et.al. Several tests were conducted on a test track using 15 subjects aged 65-80 who had to drive while calling out when they saw a particular visibility object (either a pedestrian dummy, cone, or sign). The results showed that all but two subjects saw the dummies further with the vision enhancement system than with conventional low beams. The increase ranged from 12.5m to 112.5m. The results for detecting road signs were mixed. Half the subjects saw the large road sign sooner with the vision enhancement systems and half saw it later. Another test measured visibility to an actual pedestrian moving towards a stationary car. Subjects had a large improvement in detecting the actual pedestrian. Most of the subjects regarded the system as beneficial and reported that they would use it to drive more at night.

While these findings are encouraging, it should be noted that subjects were tested under somewhat benign, controlled conditions. The critical test is whether drivers will benefit from the increased visibility under more complex, realistic situations without experiencing disbenefits. Future research is needed to determine the circumstances under which older drivers would use a VES and whether such use provides visibility benefits that allow increased mobility and safety. For example, will a narrow field-of-view further exacerbate the limited focus of attention that some older drivers experience; also, to what extent does the increased visibility provided by

VES overcome the problems that drivers have with oncoming headlight glare.

Various system design parameters may affect the net benefits. For example, the system's field-of-view will affect driver workload, comfort, and what objects will be detected. It should be noted that the older subjects in the study cited above expressed a strong desire for a wider field-of-view. Image resolution will affect the detectability of small objects. Display brightness will influence the detectability of roadway objects outside the field-of-view because the driver's eyes will not be adapted to the lower luminance of the roadway. Another display consideration, especially for far-infrared system, is that thermal imagery does not always look the same as objects viewed directly. This may affect the driver's ability to readily recognize objects and determine their distance. NHTSA is planning research to help better understand the influence of these and other parameters on driver performance with vision enhancement systems.

System Integration - As the state of development of ITS technologies advances and multiple systems are introduced in vehicles, the need to consider the integration of systems with each other becomes more critical. For example, if a driver is changing lanes and more than one warning activates, the driver needs to know quickly whether the primary threat is from the side or front. Older drivers may be particularly prone to confusion and distraction caused by the need to attend to multiple sources of information. Message priority schemes and standardized auditory warnings are examples of the requirements needed to help older drivers sort out the proper information in a timely manner.

Driver Acceptance - Research is also starting to address whether or not drivers will appreciate the benefits of in-vehicle ITS and find the systems user-friendly. Some preliminary insights are being obtained from the results of focus group discussions conducted for the U.S. Department of Transportation to explore the reactions of a small sample of the driving population, including a group of active seniors, to various crash avoidance technologies (Charles River Associates Inc., 1998). There was generally a favorable reaction to crash avoidance systems. Interestingly, the older drivers were significantly more favorable towards the concepts than the younger drivers. This was attributed to the perceived benefits of the concepts as well as the tendency to buy cars that were fully equipped with comfort and safety features. The older drivers were particularly interested in rear object detection to help them in parking lots, which is consistent with the crash statistics and increased head turning difficulty for this group.

Despite interest in the concepts, all drivers expressed some concerns about how well the technologies would work. The concerns focused on the potential for warnings to be distracting, whether there would be too many false alarms, whether the driver would be able to react in time, and whether

the sound might startle the driver. They also specifically raised the concern that over reliance on these systems might lead to drivers paying less attention to the road or compensating for the perceived safety enhancement with riskier driving (e.g., more lane changing or faster speeds). This problem is known as 'behavioral adaptation' and may be a real concern affecting the potential safety benefits of in-vehicle technologies.

## CONCLUSIONS

To some extent, the types of safety problems experienced by older drivers are similar to those of younger drivers. Thus, all driver age groups may benefit from the potential safety benefits of in-vehicle collision avoidance systems. The small number of older drivers sampled in studies to date are generally favorable to such systems but are concerned that the devices may have undesirable side effects. These side effects can be minimized and device effectiveness can be enhanced if the systems are designed to be compatible with older driver capabilities for attending to and responding to warning signals and information displays. Many studies have investigated how the physical, psychological, and physiological capabilities of older drivers affect their performance. However, the design of in-vehicle technologies would also benefit from a better understanding of when and how they drive in the real world to accommodate to their limitations. Such data can be obtained from surveys as well as *in situ* measurements of older driver behaviors during car following, lane changing, turning and other driving tasks. This paper emphasized in-vehicle safety and information systems, but other vehicle technologies may also help improve the mobility of older drivers. Such technologies include personal security systems, Mayday crash alert systems, better seating adjustment, easier ingress/egress, and systems to locate vehicles in parking lots.

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## ANTILOCK BRAKE SYSTEMS AND RISK OF DIFFERENT TYPES OF CRASHES IN TRAFFIC

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### ABSTRACT

While antilock brakes (ABS) have been convincingly demonstrated to enhance test track braking performance, their effect on crash risk in actual driving remains less clear. This paper examines how ABS influences crash risk using mainly two published studies which used police-reported crashes. The published findings are augmented by including new data and additional results. All the work is based on seven General Motors passenger vehicles having ABS as standard equipment for 1992 models but not available for 1991 models. The ratio of crashes under an adverse condition (say, when the pavement is wet) to under a normal condition (say, when the pavement is dry) is compared for ABS and *non*-ABS vehicles. After correcting for such factors as model year effects not linked to ABS, the following associations between ABS and crash risk were found by averaging data from the five states Texas, Missouri, North Carolina, Pennsylvania and Indiana (the errors are one standard error); a  $(10 \pm 3)\%$  relative lower crash risk on wet roads compared to the corresponding comparison on dry roads; a  $(22 \pm 11)\%$  lower risk of a pedestrian crash compared to the risk of a non-pedestrian crash; a  $(39 \pm 16)\%$  increase in rollover crash risk compared to the risk of a non-rollover crash. Data from the same five states were used to examine two-vehicle rear-end collisions. Using the assumption that side-impact crashes estimate exposure, it was found that for wet roads ABS reduces the risk of crashing into a lead vehicle by  $(32 \pm 8)\%$ , but increases the risk of being struck in the rear by  $(30 \pm 14)\%$ . The results from this study and from all available reported studies are summarized in tabular form.

### INTRODUCTION

Anti-lock braking systems (ABS) use electronic controls to maintain wheel rotation under hard braking that would otherwise lock a vehicle's wheels. Keeping the wheels rotating increases vehicle stability, especially when tire/roadway friction is reduced or varying, as when the pavement is wet. Prior general understanding of the relationship between improved braking and safety [1, p 282-306], together with earlier specific literature on antilock

braking, leads one to anticipate a complex interaction between ABS and safety.

Test track evaluations have convincingly demonstrated the technical advantages of ABS under a wide variety of conditions [2-4]. A study [5] analyzing historical traffic crash data for a non-ABS vehicle fleet predicted that universal ABS in Germany could diminish severe crashes by 10 to 15%. However, when taxi drivers in Munich were randomly assigned vehicles with and without ABS, no overall difference in crash rates between the two groups was observed, although each group experienced different types of crashes [6]. Because the severity of crashes apparently induced by ABS was less than that for the crashes prevented, the study suggests that the ABS system led to a net reduction in harm. An analysis of Swedish insurance data uncovered associations between the rates of occurrence of different types of crashes and ABS [7]. An analysis of Canadian insurance data found a 9% reduction in claim frequency, but a 10% increase in average claim severity [8]. The Highway Loss Data Institute [9] found no change associated with ABS in either the frequency or severity of traffic crashes. A study [10] using police-reported crashes per registered vehicle reports a 6% to 8% reduction in crash risk due to ABS, while another study using fatal crashes [11] finds an increase in risk to occupants of ABS equipped vehicles but a decrease in risk to other road users.

The present paper aims at increasing understanding about the relationship between ABS and traffic safety by summarizing the results of two recent studies [12,13], augmenting these results with additional data and findings, and then comparing the results to other results in the literature.

The first of the two studies [12] examined how ABS affects the relative risk of crashes in general under different roadway, environmental, and other conditions using data on police reported crashes from two states (Texas and Missouri). The second study [13] was confined to two-car crashes, and examined the following two questions: How does ABS affect a vehicle's risk of crashing into a vehicle it is following? How does ABS affect a vehicle's risk of being struck in the rear? This study used data from five states (Texas, Missouri, North Carolina, Pennsylvania and Indiana -- listed in the order of number of relevant crashes).

In the present paper the results of the first study are updated by including data from all five states.

## APPROACH

The ratio of the number of crashes under an adverse or unusual condition (say, when the pavement is wet) to the number of crashes under a standard, normal or comparison condition (say, when the pavement is dry) is computed for some specified group of vehicles. This wet to dry crash involvement ratio will be the same for two groups of vehicles whose crash rates are the same under either wet or dry conditions. However, the ratio is different for a group of vehicles possessing a characteristic that influences crash rate more under wet than under dry conditions. Comparing the *wet to dry* ratio for a group of ABS-equipped vehicles to the corresponding ratio for an otherwise identical group of *non*-ABS vehicles measures the influence of ABS on relative crash risk.

The comparison is relative -- a reduction in the *wet to dry* ratio occurs if ABS is associated with a decrease in the number of *wet* crashes or an increase in the number of *dry* crashes; the method cannot identify the extent to which it is changes in the numerator versus changes in the denominator that lead to the observed changes in the ratio. Purely for expository convenience and clarity, we make the temporary simple assumption that the risk under the standard condition (dry in this example) is unaffected by ABS. The results can readily be recalculated based on any assumed change in crash risk in the standard condition due to ABS.

**Table 1.**  
**ABS availability in the study vehicles**

	Model Year	
	1991	1992
Chevrolet Cavalier	No	Yes
Chevrolet Beretta	No	Yes
Chevrolet Corsica	No	Yes
Chevrolet Lumina APV	No	Yes
Pontiac Sunbird	No	Yes
Pontiac Trans Sport	No	Yes
Oldsmobile Silhouette	No	Yes

## DATA

The same seven vehicles used in the Highway Loss Data Institute study [9] (Table 1) provide the data for this study. All are GM passenger vehicles that did not offer ABS in 1991 models, but had ABS as standard equipment in 1992 models. Thus the comparison is between the crash risks of the 1992 model year (MY) vehicles and the 1991 MY versions of these vehicles.

In all the analyses presented here, data for calendar years 1992 and 1993 are combined.

## CALCULATIONS

The calculation procedures used are described in terms of the specific example of comparing crashes when the pavement is wet to when the pavement is dry using numerical values from the Texas data. We first estimate the quantity  $R_1$ , defined as

$$R_1 = \frac{A_{\text{wet}}}{A_{\text{dry}}} \div \frac{N_{\text{wet}}}{N_{\text{dry}}} \quad (1)$$

where  $A$  = Number of crashes by ABS-equipped vehicles, and

$N$  = Number of crashes by *non*-ABS-equipped vehicles,

and the subscripts indicate the pavement condition when the crashes occurred. The Texas data provide the following values:

$$A_{\text{wet}} = 579$$

$$N_{\text{wet}} = 1219$$

$$A_{\text{dry}} = 3118$$

$$N_{\text{dry}} = 4865$$

These values show that  $579/(579+3118) = 15.7\%$  of the crashes by ABS-equipped vehicles occurred on wet pavement, compared to  $20.0\%$  for the *non*-ABS vehicles. Substituting into eqn 1 gives

$$R_1 = 0.7411 \quad (2)$$

If the ABS and *non*-ABS vehicles differed in no other characteristics that could affect crash involvement risk, then  $R_1$  would measure directly the influence of ABS. The value  $R_1 = 1$  indicates no effect,  $R_1 < 1$  indicates reduced risk for ABS vehicles on wet roads, and  $R > 1$  indicates increased risk for ABS vehicles (assuming that ABS does not affect crash risk on dry roads). The above values suggest a  $25.89\%$  reduction in crash risk on wet roads for the ABS vehicles. However, such an inference is invalid because of the presence of two important biasing effects.

## Two biasing, or confounding, interactions

First, a *model year effect*. The ABS-equipped vehicles are all model year 1992, whereas the *non*-ABS vehicles are all model year 1991. Thus, the typical *non*-ABS crash compared to the typical ABS crash involved a vehicle approximately one year older. It is well established that crash rates depend systematically on vehicle age [14].

Second, what might be referred to as a *ramp-up effect*. By the beginning of the period for which crashes are included in the data, namely 1 January 1992, nearly all the 1991 MY vehicles were already registered. Hence, throughout calendar year 1992 they were all exposed to risk. In contrast, by 1 January 1992 few 1992 MY vehicles had been registered. As calendar year 1992 progresses from January to December, the number of 1992 MY vehicles registered steadily increases. As the roadway and weather conditions on which this study focuses change throughout the year, this ramp-up effect could introduce serious bias. For example, if there was much snow in January 1992, this would generate many crashes on snow by the already present 1991 MY vehicles. However, the 1992 MY vehicles not yet registered cannot experience these crashes, thus biasing  $R_1$  downwards, and inviting a false attribution of reduced crashes to ABS rather than the ABS vehicles being not exposed.

## Estimate of influence of ABS on relative risk

The model year effect and the ramp-up effect can both be corrected for by computing a second ratio,  $R_2$ , defined as

$$R_2 = \frac{92MY_{wet}}{92MY_{dry}} \div \frac{91MY_{wet}}{91MY_{dry}}, \quad (3)$$

where 92MY = Number of crashes by 1992 model year vehicles,  
91MY = Number of crashes by 1991 model year vehicles.

The seven makes in Table 1 are excluded from the computation of  $R_2$ . The Texas data provide the following values:

$$\begin{aligned} 92MY_{wet} &= 16,509 & 91MY_{wet} &= 21,715 \\ 92MY_{dry} &= 72,361 & 91MY_{dry} &= 85,810. \end{aligned}$$

So  $R_2 = 0.9016$ . This indicates that 1992 model year vehicles have, compared to 1991 model year vehicles, 9.8% lower crash risk when the pavement is wet compared to when it is dry; such model year effects of this magnitude are to be expected [1, 14].

An estimate,  $R$ , of the effect of ABS on crash rate correcting for the two confounding biases is defined by

$$R = R_1/R_2, \quad (4)$$

which, for the present example gives  $R = 0.7411/0.9016 = 0.8220$ . In using this measure we make the plausible assumption that the ramp-up effect for the ABS vehicles is the same as for 1992 model year vehicles in general. This is equivalent to assuming that the probability that a vehicle of specific model year was registered by a given month is independent of whether or not it has ABS.

It is often convenient to think of the percent reduction,  $E$ , in relative risk for ABS compared to *non*-ABS, defined as

$$E = 100(1 - R)\%. \quad (5)$$

For the present example,  $E = 100(1 - 0.8220)\%$ , or  $E = 17.80\%$ . That is, ABS is associated with a 18% lower crash risk on wet pavement. The interpretation of  $E$  is similar to an effectiveness as defined for devices such as safety belts [1]. Positive values indicate a reduction in risk, and negative values an increase in risk.

## General terminology

To facilitate comparisons between any unusual (adverse) condition and any standard (normal or comparison) condition, and to simplify error calculations, we introduce the following terminology (the corresponding quantities for the specific example are indicated in parenthesis):

- $n_1$  = No. of crashes by ABS-equipped vehicles under the unusual condition (corresponds to  $A_{wet}$ )
- $n_2$  = No of crashes by ABS-equipped vehicles under the standard condition ( $A_{dry}$ )
- $n_3$  = No. of crashes by *non*-ABS-equipped vehicles under the unusual condition ( $N_{wet}$ )
- $n_4$  = No of crashes by *non*-ABS-equipped vehicles under the standard condition ( $N_{dry}$ )
- $n_5$  = No. of crashes by 1992 Model Year vehicles under the unusual condition ( $92MY_{wet}$ )
- $n_6$  = No of crashes by 1992 Model Year vehicles under the standard condition ( $92MY_{dry}$ )
- $n_7$  = No. of crashes by 1991 Model Year vehicles under the unusual condition ( $91MY_{wet}$ )
- $n_8$  = No of crashes by 1991 Model Year vehicles under the standard condition ( $91my_{dry}$ ).

In terms of the above quantities R is defined as

$$R = \frac{n_1 \times n_4 \times n_6 \times n_7}{n_2 \times n_3 \times n_5 \times n_8} \quad (6)$$

## Errors in R and E

In defining R (and  $R_1$  and  $R_2$ ), it is arbitrary whether we compare wet to dry, or dry to wet. If, say, the risk when wet was 2.0 times the risk when dry, then the risk when dry would be 0.5 times the risk when wet. The quantity R has a logical lower bound of zero, but no logical upper bound (E can be in the range from  $-\infty$  to 100%). Accordingly, the errors around the estimate of R (or E) are not symmetric. A measure possessing the desired symmetry is the log odds ratio [15], the logarithm of R. If we choose natural logarithms (to base e), represented by  $\ln(R)$ , then the standard error in the log odds ratio,  $\sigma_{\ln(R)}$ , is given by

$$\sigma_{\ln(R)} = \sqrt{\sum_{i=1}^8 \frac{1}{n_i}} \quad (7)$$

where the summation is over the eight crash frequencies used to compute R. Substituting the specific example values gives  $\sigma_{\ln(R)} = 0.0566$ . The major contribution to the error comes from the smallest number (in this case,  $n_1 = 579$ ). The larger numbers, such as  $n_8 = 85,810$  make a negligible contribution to the error. The upper and lower error limits on R are given by

$$R_{\text{lower limit}} = \exp[\log(R) - \sigma_{\ln(R)}] \quad (8)$$

$$R_{\text{upper limit}} = \exp[\log(R) + \sigma_{\ln(R)}] \quad (9)$$

For the illustrative example,  $R_{\text{lower limit}} = 0.7768$  and  $R_{\text{upper limit}} = 0.8699$ . Using eqn 5 we can express these values equivalently as  $E_{\text{lower limit}} = 13.01\%$  and  $E_{\text{upper limit}} = 22.32\%$ . The lower limit of E corresponds to the upper limit of R.

When errors are small, the standard error in E,  $\Delta E$ , is given approximately by

$$\Delta E = 100 \times R \times \sigma_{\ln(R)} \quad (10)$$

which for the example is  $100 \times 0.8222 \times 0.0566 = 4.65\%$ .

For this example the result  $E = (17.80 \pm 4.65)\%$  is nearly identical to the result from computing the upper and lower limits individually. Results will generally be presented in

this convenient  $(E \pm \Delta E)\%$  form. When errors are too large for this approximation to be adequate, upper and lower limits will be given in the text.

All errors quoted are standard errors. The approximate interpretation is that the actual value is 68.26% likely to be within the quoted error limits, but has a 15.87% chance of being either higher or lower. Two standard errors correspond approximately to a 95% confidence limit (rather than the present 68%), and three standard errors to a 99% confidence limit.

## RESULTS FOR OVERALL CRASH RISK

### Roadway surface

The specific example used to illustrate the calculations appears as the top item in Table 2, and shows a  $(17.8 \pm 4.7)\%$  lower risk for ABS-equipped vehicles on wet roads. As the effect is well over three standard errors different from zero, it is extremely likely that ABS does reduce crash risk on wet roads. The combined estimate for a groups of states is obtained by adding the raw data from each of the states. This is equivalent to assuming that one composite jurisdiction provided all the data. Conceptually and computationally, this is the simplest procedure. In order to facilitate comparison with the previously published results in [12], the result for Texas and Missouri combined is given. All the raw data used for these states are given in [12].

**Table 2.**  
Results for different roadway surface conditions  
compared to dry roadway

Condition	State	E $\pm$ $\Delta E$ , %
Wet	Texas	17.8 $\pm$ 4.7
	Missouri	5.7 $\pm$ 7.2
	TX & MO combined	13.0 $\pm$ 3.9
	North Carolina	4.5 $\pm$ 8.0
	Pennsylvania	13.8 $\pm$ 7.1
	Indiana	3.8 $\pm$ 7.8
	All 5 states combined	10.4 $\pm$ 2.7
Snow or ice	Texas	26.6 $\pm$ 20.3
	Missouri	-3.3 $\pm$ 16.0
	TX & MO combined	3.7 $\pm$ 12.8
	North Carolina	0.5 $\pm$ 41.2
	Pennsylvanian	2.1 $\pm$ 12.2
	Indiana	11.5 $\pm$ 13.9
	All 5 states combined	6.3 $\pm$ 7.1

All five states have positive values of E, giving the composite result that ABS reduces crash risk on wet roads by  $(10 \pm 3)\%$  (assuming no change in crash risk on dry roads).

When the roadway surface is snow or ice covered, sample sizes are substantially smaller, and a less clear pattern emerges. The composite estimate of  $(6 \pm 7)\%$  at most hints that ABS may reduce crash risk when the road is snow or ice covered.

## Weather

Given that the road surface is coded as wet, there is about a 70% probability that the weather is coded as rain. Results for rain and other weather conditions are presented in Table 3. The results for all five states consistently indicate that ABS is associated with a reduced risk of crashing when it is raining (assuming no effect under clear weather). The combined result,  $(12 \pm 2)\%$ , is very similar to the result on wet compared to on dry pavement. No clear pattern emerges from the analyses of the other weather conditions shown in Table 3.

**Table 3.**  
**Results for different weather conditions compared to clear (including cloudy) weather**

Condition	State	E $\pm$ $\Delta$ E, %
Rain	Texas	15.9 $\pm$ 5.6
	Missouri	8.7 $\pm$ 8.3
	TX & MO combined	12.8 $\pm$ 4.7
	North Carolina	6.6 $\pm$ 8.8
	Pennsylvania	20.0 $\pm$ 7.3
	Indiana	2.1 $\pm$ 9.5
	All 5 states combined	11.6 $\pm$ 2.4
Snow, Ice, Sleet, or Freezing	Texas	60.9 $\pm$ 16.7
	Missouri	-5.0 $\pm$ 18.7
	TX & MO combined	9.6 $\pm$ 14.4
	North Carolina	-26.1 $\pm$ 56.4
	Pennsylvania	4.9 $\pm$ 13.1
	Indiana	-22.9 $\pm$ 19.0
	All 5 states combined	-0.9 $\pm$ 8.4
Fog	Texas	-39.1 $\pm$ 33.2
	Missouri	40.4 $\pm$ 18.6
	TX & MO combined	0.0 $\pm$ 18.6
	North Carolina	43.9 $\pm$ 27.1
	All 3 states combined	7.6 $\pm$ 16.0

## Rollover risk

Table 4 shows results of comparing crashes involving overturn to all crashes except those involving overturn (essentially comparing rollover crashes to all crashes). Data from four of the five states associate ABS-equipped vehicles with increased rates of rollover crashes. The results for Texas and Indiana are, individually, close to two standard errors different from no effect. The composite effect is that the ABS-equipped vehicles have a  $(39 \pm 16)\%$  higher relative rollover risk. The one standard error lower and upper limits more appropriately computed by eqns 8 and 9 are 23% and 56%, respectively; the two standard

**Table 4.**

**Results for crashes involving overturn, pedestrians, or animals. In each case the comparison is between crashes involving the stated factor and all other crashes not involving it. For example, all crashes in which the vehicle overturned are compared to all crashes in which the vehicle did not overturn.**

Condition	State	E $\pm$ $\Delta$ E, %
Overturn	Texas	-50.7 $\pm$ 26.2
	Missouri	-27.1 $\pm$ 40.5
	TX & MO combined	-44.4 $\pm$ 22.0
	North Carolina	-9.1 $\pm$ 29.1
	Pennsylvania	25.9 $\pm$ 39.4
	Indiana	-92.5 $\pm$ 59.0
	All 5 states combined	-38.7 $\pm$ 16.3
Pedestrian	Texas	36.6 $\pm$ 17.7
	Missouri	29.8 $\pm$ 26.9
	TX & MO combined	33.9 $\pm$ 14.9
	North Carolina	-49.2 $\pm$ 68.4
	Pennsylvania	11.8 $\pm$ 19.6
	Indiana	41.5 $\pm$ 26.9
	All 5 states combined	22.2 $\pm$ 11.0
Animal	Texas	-27.7 $\pm$ 35.1
	Missouri	-15.8 $\pm$ 29.3
	TX & MO combined	-20.8 $\pm$ 22.4
	North Carolina	7.7 $\pm$ 17.2
	Pennsylvania	28.8 $\pm$ 27.4
	Indiana	3.4 $\pm$ 14.5
	All 5 states combined	-1.2 $\pm$ 9.6

error limits are 10% to 75%. If there were no effect, the probability that a value of R as large as observed would arise by chance is less than 1%. The data establish with some confidence that a higher relative rollover risk is associated with ABS.

## Crashes with Pedestrians and Animals

Data from four of the five states associate ABS with a lower risk of pedestrian crashes (Table 4). The combined effect is  $(22 \pm 11)\%$ . The one standard error lower and upper limits more appropriately computed by eqns 8 and 9 are 11% and 32%, respectively; the 1.96 standard error limits are -3% and 41%, so the effect falls just short of being statistically significantly different from zero at the 5% confidence limit.

There are no consistent effects relating ABS and crashes involving animals (Table 4), though Kahane finds ABS associated with reduced risk of crashing with pedestrians and animals [16], and Farmer et. al [11] find a reduction in the risk of killing pedestrians, bicyclists and occupants of other vehicles. No associations between the risk of any type of injury and ABS were found [12]. The main results presented above are summarized in Table 5; the minor differences from Table 8 of [12] arise because of the addition of the data from NC, PA, and IN.

**Table 5.**

**Summary of effects of ABS on some relative crash risks**

Condition investigated	Comparison condition	Risk reduction associated with ABS
Wet roadway	Dry roadway	$(10 \pm 3)\%$
Raining	Clear or cloudy weather	$(12 \pm 2)\%$
Crashes involving pedestrians	All crashes not involving pedestrians	$(22 \pm 11)\%$
Crashes involving overturn	All crashes not involving overturn	$-(39 \pm 16)\%$

## RISK OF FRONT AND REAR IMPACT IN TWO-VEHICLE CRASHES

Similar analysis procedures were used to investigate two-vehicle crashes in the same five states [13]. Each crash

included in the analysis had a clearly defined lead vehicle (identified by rear damage) and a following vehicle (identified by frontal damage), thus enabling us to address the following questions: -

1. How does ABS affect a vehicle's risk of crashing into a vehicle it is following?
2. How does ABS affect a vehicle's risk of being struck in the rear?

## Approach

Two sets of calculations were performed. In the first the influence of ABS on the ratio of front to rear impacts was determined. Let us call this the *Front-to-Rear* ratio. If it is assumed that ABS has no effect on the risk of being struck in the rear, then a lower *Front-to-Rear* ratio implies that ABS reduces the risk of striking a lead vehicle. However, if ABS has no effect on risk of striking a lead vehicle, then a lower *Front-to-Rear* ratio implies that ABS increases the risk of being struck in the rear. The *Front-to-Rear* ratio is a relative risk measure which does not distinguish between reduced front or increased rear impacts. However it has the advantages that it uses data efficiently, and its interpretation does not involve additional uncertain assumptions.

In the second set of calculations an attempt was made to estimate a more absolute risk of front and rear impacts by normalizing with respect to another crash type less likely to be influenced by ABS than either front or rear impacts. The other crash mode chosen was side impacts; this is equivalent to using side impacts as an induced exposure measure.

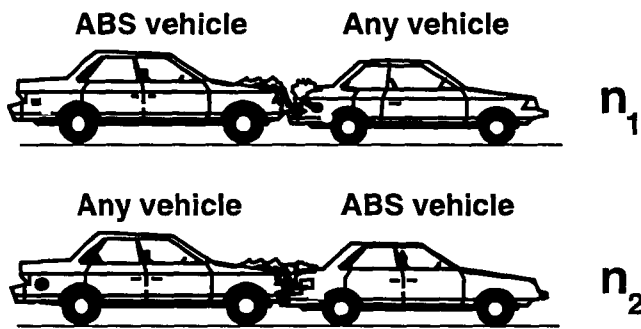
## Calculations

Figure 1 illustrates the two crash types that are at the core of [13]. These crash types are more formally defined as

$n_1$  = the number of crashes in which an ABS-equipped vehicle sustained frontal damage in crashing into the rear of any vehicle

$n_2$  = the number of crashes in which an ABS vehicle was struck in the rear by any vehicle.

For any complete set of two-vehicle crashes (confined to one vehicle frontally striking another in the rear), the total number of vehicles struck in the rear is, by definition, identical to the total number of vehicles struck in the front. However, for subsets of crashes involving specific vehicles, no such equality applies. Rather, the departure from equality measures a differential tendency to be involved as either a striking or a struck vehicle.



**Figure. 1.** Definitions of the two main crash types used to compute the *Front-to-Rear* ratio

We illustrate the calculation procedures using one specific numerical example, namely, Texas crashes on wet roads. For this case we have  $n_1 = 44$  and  $n_2 = 75$ . These values nominally indicate that the ABS vehicles are 0.59 times as likely to be struck in the front as in the rear. However, this difference cannot be attributed to ABS alone. The *non*-ABS versions of the seven specific vehicles contributing to the study are not expected to have identical numbers of front and rear impacts (*non*-ABS refers to the 1991 model year versions of the seven vehicles in Table 1, and not to other vehicles without ABS). We must therefore compare the ratio of  $n_1$  to  $n_2$  for the ABS vehicles to the corresponding ratio for these same vehicle makes without ABS. To achieve this we introduce

$n_3$  = the number of crashes in which a *non*-ABS-equipped vehicle sustained frontal damage in crashing into the rear of any vehicle, and

$n_4$  = the number of crashes in which a *non*-ABS vehicle was struck in the rear by any vehicle.

For Texas  $n_3 = 151$  and  $n_4 = 108$ , so that on wet roads the *non*-ABS vehicles were 1.40 times as likely to be struck in the front as in the rear. The large departure of this ratio from unity reflects a general pattern in which on wet roads smaller cars have large *Front-to-Rear* ratios whereas large cars and trucks have small *Front-to-Rear* ratios. This pattern was found to be highly robust, based on considerable analyses of the same state data used in this study. To obtain the effect of ABS we divide the *Front-to-Rear* for the ABS vehicles by the corresponding ratio for the *non*-ABS vehicles. Therefore, we obtain the result that, compared to the *non*-ABS vehicles, the ABS vehicles are  $0.59/1.40 = 0.42$  times as likely to be struck in the front as in the rear.

The above comparison of ABS and *non*-ABS vehicles involved comparing risks in 1992 to risks in 1991 model year vehicles. As there are systematic differences dependent on model year [1,14], we correct for this model year effect by introducing

$n_5$  = the number of crashes in which a 1992 MY vehicle sustained frontal damage in crashing into the rear of any vehicle

$n_6$  = the number of crashes in which a 1992 MY vehicle was struck in the rear by any vehicle

$n_7$  = the number of crashes in which a 1991 MY vehicle sustained frontal damage in crashing into the rear of any vehicle

$n_8$  = the number of crashes in which a 1991 MY vehicle was struck in the rear by any vehicle.

The values for Texas on wet roads are:  $n_5 = 1703$ ;  $n_6 = 2130$ ;  $n_7 = 2345$ ; and  $n_8 = 2626$ . These values give  $n_5/n_6 + n_7/n_8 = 0.89$ , which means that 1992 MY vehicles are, compared to 1991 MY vehicles, 0.89 times as likely to be struck in the front as to be struck in the rear. Dividing the previous 0.42 ratio by this value gives that the ABS vehicles are 0.47 times as likely to be struck in the front compared to being struck in the rear. Thus, we find that on wet roads in Texas, there is a *Front-to-Rear* ratio of 0.47 that is specifically attributable to ABS, or, equivalently,  $E = 53\%$ .

The above calculation of the *Front-to-Rear* ratio,  $R$ , can be stated more formally as

$$R = \frac{n_1 \times n_4 \times n_6 \times n_7}{n_2 \times n_3 \times n_5 \times n_8} \quad (11)$$

This is identical to eqn 6 (with the present definitions of  $n_1$  through  $n_8$  replacing the earlier definitions), so the computation of errors and other quantities follow as before.

## RESULTS FOR WET ROADS

### Ratio of Front Impact to Rear Impact crashes

The example above appears as the first entry in Table 6. The corresponding results for the other four states are entered below this value (the raw numbers from which all values in Table 6 were computed are given in [13]). For all five states  $E$  is positive. For TX and MO the values of  $E$  have high statistical reliability, being 3.2 and 5.3 standard errors different from no effect. The probabilities that the  $E$  values for the remaining three states (NC, PA, & IN) are individually positive are 65%, 91%, and 92% (compared to 56%, 9%, and 8%, respectively, that they are negative). Thus all the five states show consistently that on wet roads a vehicle with ABS is less likely to crash into a vehicle it is following compared to its own risk of being struck in the rear. The result of combining the data from all five states is  $E = (48.0 \pm 6.0)\%$ .

**Table 6.**  
**Two vehicle crash results for WET roads.**

State	Reduction in risk for ABS vehicles, $E \pm \Delta E$ (%)				
	<u>Front</u> <u>Rear</u>		<u>Front</u> <u>Side</u>	<u>Rear</u> <u>Side</u>	
	All lead vehicles	Lead vehicle stopped	Lead vehicle moving	All lead vehicles	All lead vehicles
TX	52.8 (11.0) <sup>①</sup>	63.6 (11.3)	50.8 (23.2)	38.8 (12.3)	-29.7 (23.7)
MO	79.8 ( 6.0)	75.1 (11.0)	83.4 ( 7.7)	64.8 (10.3)	-74.1 (39.3)
NC	11.0 (26.5)	42.3 (23.8)	24.0 (44.4)	22.5 (23.0)	12.9 (25.3)
PA	31.0 (19.2)	16.6 (34.8)	*	40.2 (23.0)	13.3 (32.4)
IN	28.5 (17.0)	38.6 (30.2)	24.0 (31.6)	25.8 (22.5)	-3.9 (30.6)
ALL	48.0 ( 6.0)	55.5 ( 7.9)	57.2 ( 9.8)	32.2 ( 7.7)	-30.4 (13.6)

① One standard error shown in parenthesis

\* Insufficient data

The individual state results vary somewhat more than expected by chance in this case, in keeping with generally observed differences between quantities observed in different state files. In terms of 95% confidence limits, only the MO result (R between 0.11 and 0.36) is inconsistent with the overall average (R between 0.41 and 0.65). It could be argued that, from a formal statistical viewpoint, it is inappropriate to aggregate data showing such a degree of heterogeneity, and that the only results that should be reported are those for individual states. Hauer [17] presents convincing arguments opposing this view, and stresses the central importance of providing aggregate estimates even in the face of formal obstacles. Because of the heterogeneity in the results from the individual states, the standard error of the aggregate estimate will be underestimated. One way to obtain a more appropriate standard error would be to increase the estimates of the standard errors of the individual states by a quantity reflecting a judgmental estimate of the effect of sources of variability beyond those due to statistical fluctuations in the frequency counts [18]. Because of the arbitrary nature of the choice of the additional variability for each state, we will not do this here. The aggregate estimate

we use was obtained by adding the raw data, which is equivalent to assuming that one composite jurisdiction provided all the data; conceptually and computationally, this is the simplest procedure. Another way to obtain a composite estimate is to assume that each state provides an independent estimate, and obtain an average by weighting each state estimate by the reciprocal of the square of its standard error. Such a procedure [19] yields  $(45.8 \pm 6.4)\%$ , not materially different from the result  $(48.0 \pm 6.0)\%$  which we use.

The result  $E = (48.0 \pm 6.0)\%$  is 5.6 standard errors different from no effect. Thus, even with the reservation that the standard error may be somewhat underestimated, this result still provides evidence at an extremely high level of reliability of a substantial difference dependent on the presence of ABS. If we assume that ABS does not affect the risk of being struck in the rear, then it essentially halves the risk of crashing into a lead vehicle. It is rare for an effect of this magnitude to be associated with any vehicular attribute.

**Lead vehicle stopped.** When the lead vehicle is coded as being stopped (but not parked) the five states again consistently show large positive values of E (Table 6). The combined result for all five states is that on wet roads an ABS-equipped vehicle is  $(55.5 \pm 7.9)\%$  less likely to run into the rear of a stationary vehicle than it is to be struck in the rear when stationary. Note that the probability that a stationary vehicle is struck in the rear is expected to depend somewhat on its braking capabilities. The greater the stopping deceleration used, the longer is the period during which the vehicle is stationary. Observational studies [20] found newer cars used higher levels of deceleration when stopping at intersections, an effect likely related to superior braking capability, and a pattern likely to increase the risk of being rear impacted.

**Both vehicles moving.** For the case in which both vehicles were coded as moving in the same (forward) direction there were insufficient cases in PA to perform this analysis. The four remaining states consistently show large positive values of E, with a combined result that on wet roads an ABS-equipped vehicle is  $(57.2 \pm 9.8)\%$  less likely to run into the rear of a moving lead vehicle than it is itself to be struck in the rear when moving.

### Use of Side Impact Crashes to Estimate Absolute Effects of ABS

The above estimates are all relative in the sense that the risk of front impact is expressed only relative to the risk of rear impact. A value of  $E = 50\%$  could arise if ABS halved the risk of crashing into a lead car while not affecting the risk of being rear impacted. However, the identical value would arise if ABS did not affect the risk of crashing into a lead vehicle, but doubled the risk of being rear impacted. In



order to separate the two components of the *Front-to-Rear* ratio, we use an induced exposure measure, in which the number of side impacts sustained by a set of vehicles is used to estimate the presence of those vehicles in the traffic stream. Using side impact crashes to measure exposure involves the crucial assumption that the risk of a vehicle being struck in the side is not affected by whether or not the vehicle is equipped with ABS. While such an assumption is clearly an approximation, it is nonetheless likely to be sufficiently correct to identify large effects.

The *Front-to-Side* ratio has positive values of *E* for all five states, implying that on wet roads a vehicle equipped with ABS is less likely to crash into a vehicle it is following than is a vehicle not so equipped (Table 6). The calculation is as before, except that  $n_2$ ,  $n_4$ ,  $n_6$ , and  $n_8$ , refer to crashes in which the vehicle is struck in the side rather than in the rear. Combining the data for all states gives the result that ABS reduces the risk of crashing into a lead vehicle by  $(32.2 \pm 7.7)\%$ .

For the *Rear-to-Side* ratio the results for MO and TX are statistically significantly different from zero effect at the  $p < 0.01$  and  $p < 0.1$  levels of confidence, respectively, and each indicates an increased risk of being struck in the rear to be associated with ABS. The uncertainty (due to small sample sizes) for the other states is too great to suggest any effect. Combining data for all five states gives the result that an ABS equipped vehicle is  $(30.4 \pm 13.6)\%$  more likely to be struck in the rear than a vehicle without ABS.

## RESULTS FOR DRY ROADS

Table 7 summarizes the results of an analysis parallel to that described above, but for crashes on dry roadway. Overall *Front-to-Rear* ratio shows no indication of any effect dependent on ABS. For the case of both vehicles moving, there is a suggestion of an increased risk of crashing into the rear of a lead car.

Table 7.  
Two vehicle crash results for DRY roads

Reduction in risk for ABS vehicles, $E \pm \Delta E$ (%)					
State	<u>Front</u> <u>Rear</u>			<u>Front</u> <u>Side</u>	<u>Rear</u> <u>Side</u>
	All lead vehicles	Lead vehicle stopped	Lead vehicle moving	All lead vehicles	All lead vehicles
TX	-4.6 (11.2) <sup>①</sup>	1.6 (14.2)	-22.9 (25.6)	-4.8 (8.8)	-0.2 (9.0)
MO	5.8 (14.3)	1.8 (22.4)	3.3 (22.5)	-4.4 (14.2)	-10.8 (14.9)
NC	12.6 (15.6)	30.1 (16.9)	-41.5 (50.9)	-6.7 (17.1)	-22.1 (18.5)
PA	3.5 (14.6)	4.0 (21.2)	*	25.7 (14.5)	23.0 (15.0)
IN	-11.8 (17.0)	33.4 (22.4)	-53.0 (40.9)	-1.0 (17.9)	9.7 (16.1)
ALL	0.1 (6.3)	10.3 (8.4)	-23.2 (15.4)	-2.6 (5.7)	-2.7 (5.7)

① One standard error shown in parenthesis

\* Insufficient data

## IS ABS ASSOCIATED WITH INCREASED AVERAGE TRAVEL SPEED?

The earlier papers [12,13] raised the possibility that ABS (and braking improvements in general) might be associated with increased average travel speed. Such an effect would help explain why observed reductions in crash rates are generally less than those expected based on the technical improvements in braking provided by ABS.

## Inference from anecdotal information

I have asked audiences attending a number of technical presentations if they thought their driving changed because their vehicle was ABS-equipped, and have posed the same question to many acquaintances (neither group is a random sample of drivers). The following observations are based on a few hundred responses.

1. None indicated with confidence that they ever drove slower under any conditions because their vehicle was ABS-equipped.
2. Many indicated that, under certain circumstances, they were confident that they sometimes drove faster if their vehicle was ABS-equipped.

I can personally attest that I am unaware of any case in which I have ever driven slower because my vehicle had ABS. On the other hand, I have driven faster on many occasions because my vehicle was ABS equipped. For example, when driving on slush on a narrow two lane road, with oncoming traffic a few feet to my left and a deep drainage ditch a few feet to my right. My experience with non-ABS brakes tells me to severely reduce speed because even light non-ABS braking could place me in the path of uncoming traffic or in the ditch. My speed reduction is far larger than appropriate for a vehicle with the excellent lateral control that ABS so effectively provides. (My comment on page 310 of [1] that this researcher of traffic crashes has never actually experienced one remains intact at time of writing). ABS is a successful and effective automotive technology that drivers can use to increase mobility efficiency as well as safety.

The above audience, acquaintances, and personal anecdotal information suggests the following two postulates:

Postulate 1: No drivers ever drive slower because their vehicles have ABS.

Postulate 2: Some drivers, under some circumstances, sometimes drive a little faster because their vehicles have ABS.

If we accept these two postulates, then it follows with rigorous logic that, on average, all other factors being equal, ABS-equipped vehicles are driven at higher average speeds than non-ABS vehicles.

Postulate 1 need not be satisfied for the conclusion to follow provided the speed increase exceeds the speed decrease (both appropriately weighted). Thus the conclusion that ABS is associated with an increase in average speed should be viewed as inescapable. However, it is the magnitude of the effect, and the circumstances under which it occurs, that is crucial for safety.

### Preliminary examination of ABS and speed law convictions using Oregon data

An attempt was made to examine empirically whether ABS-equipped vehicles were associated with higher rates of conviction for speed-related offenses than were non-ABS vehicles. Data were obtained from Oregon because this state's files enabled linkage between driving records and vehicle ownership.

Table 8 shows convictions by drivers who were owners of 1991 or 1992 models of the seven vehicles listed in Table 1. The nominal indication is that the drivers who owned ABS

vehicles had  $(18 \pm 10)\%$  more convictions for speeding, compared to non-speeding offenses than the non-ABS vehicles. From a formal statistical perspective this is a clear effect. The data were used to examine only one hypothesis, and this hypothesis was stated prior to obtaining the data, and turns out to be statistically significant at  $p < 0.05$ . However, for two main reasons the result should be interpreted with the utmost caution.

Table 8.

**Oregon police convictions for offenses relating to excessive speed compared to other offenses for drivers who were registered owners of the ABS and non-ABS model vehicles listed in Table 1**

	Number of convictions by drivers who own:-	
	ABS vehicles	non-ABS vehicles
Speed offenses	670	801
Unrelated to speed	419	591
<u>Speed offenses</u> Non-speed offenses	1.60	1.36

First, some unknown fraction of the convictions were obtained driving a different vehicle than the one indicated (the driver may have owned additional vehicles, or have driven a borrowed vehicle). The convictions file did not contain vehicle information as such. It included the driver license. The driver license number of the registered owner was also included in the vehicle file. It can be argued that an effect such as this would tend to dilute the strength of any real effect, so that if the sample could be confined exclusively to convictions in the indicated vehicles, the effect would be larger.

Second, there is the even more important problem that the effect apparent in Table 8 could be due to the ABS and non-ABS vehicles being also of different model year. There is reason to expect differences in driver behavior to be associated with model year regardless of ABS [1,14], effects that were corrected for in [12,13]. The limited scope of this pilot examination precluded obtaining the necessary data to normalize for model year effects unrelated to ABS.

Because of the substantial uncertainties in interpretation and the caveats expressed above, the data in Table 8 should be interpreted as little more than suggesting the possibility of an effect of sufficient magnitude to justify a more complete and rigorous investigation along similar lines in the hope of further illuminating the relationship between ABS and travel speed, and of broader driver behavior questions.

## DISCUSSION

When driving on wet pavement ABS is associated with a  $(10.4 \pm 2.7)\%$  reduction in crash risk, assuming that ABS has no effect on crash risk on dry pavement. If we assume that 20% of all crashes occur on wet roads, then this result implies that ABS would reduce crash risk, overall, by  $(2.1 \pm 0.5)\%$ . Such an effect is consistent with earlier studies that reported no observed effect, because the data and methods of those studies [6,9] lacked the precision necessary to detect a reduction of this size. A reduction of 2% is of course an important effect, if real. The conclusion that such a reduction is real depends on the assumption that ABS has no effect on crash risk when the road is dry; one study [10] reports a 6% to 8% reduction on dry roads.

The finding that ABS equipped cars were associated with a  $(39 \pm 16)\%$  higher rollover risk could be due to a combination of factors. It is possible that the improved steering control provided by ABS could in some circumstances convert non-rollover crashes into rollover crashes. For example, a high-speed out of control non-ABS car might be immobilized after striking a tree, whereas if ABS were available, the greater steering control might enable the driver to miss the tree and thereby continue to travel at high speed in off-roadway terrain with consequent risk of rollover. It is possible that the very steering control that ABS provides allows steering inputs that translate into rollover, whereas the non-ABS-equipped vehicle will skid out of control until striking some object. It is also possible that ABS is associated with some small change in driver behavior which increases rollover risk, a likely candidate being a small increase in average travel speed. Anecdotal evidence and an uncertain and tentative analysis of some Oregon traffic conviction data support such a possibility. Test track experiments provide direct evidence that drivers of vehicles equipped with ABS choose higher travel speeds [21].

An investigation of the vehicle-following behavior of 213 taxis in Norway found that drivers of ABS-equipped vehicles followed at shorter headways than did those without ABS [22]. Speed was too constrained by traffic conditions to allow any effects due to ABS to be examined in this study. However, earlier research [1,23] finds that crash rates are related to headways and to travel speeds in similar ways. Thus [22] can be interpreted to provide indirect evidence that ABS is associated with higher speeds.

The finding in [8] of an increase in claim severity is likewise consistent with the possibility of increased speed. Because rollover risk is extremely sensitive to travel speed, even a small speed increase could produce a large increase in rollover risk. If such a small increase in travel speed was associated with ABS, then average crash risk on dry roads might be slightly higher, perhaps by a percent or so. It would be extremely difficult to address this question directly. Increased speeds in test-track experiments may not

necessarily translate into increased speeds in actual driving. In this regard it is notable that a 1% increase in speed has been observed to be associated with safety-belt wearing in an instrumented vehicle study [24]. Changes of this magnitude are important, but extremely difficult to observe directly in actual traffic.

How reasonable is it to expect that the availability of ABS might lead to changes in driver behavior? The 1938 volume of the American Journal of Psychology contains the following comment:

**More efficient brakes on an automobile will not in themselves make driving the automobile any safer. Better brakes will reduce the absolute size of the minimum stopping zone, it is true, but the driver soon learns this new zone and, since it is his field-zone ratio which remains constant, he allows only the same relative margin between field and zone as before. [25]**

Research conducted in the more than half a century since this was written does not support the implied suggestion that improved braking cannot affect overall crash risk. However, it does establish that technical innovations that lead to observable differences in vehicle performance or handling characteristics are likely to be accompanied by changes in driver behavior.

An extensive discussion such human behavioral responses is given in Chapter 11 of [1]. Because of the self-controlled nature of the driving task, the driver may use technical improvements to generate benefits other than safety. Two observational studies [14,20] indirectly suggest that improved braking may be used for purposes other than safety. In both, car age serves as a surrogate for braking, because it is plausible that as vehicles age, their stopping distances increase as tires and brakes deteriorate.

Observed driver behavior [20] at two signalized intersections showed that when cars stopped, drivers of newer cars used higher levels of deceleration than drivers of older cars. When cars proceeded, drivers of newer cars were more likely than were drivers of older cars to enter the intersections after the onset of red (that is, to be in violation of the traffic code). The authors write "It is possible that the drivers of older vehicles are adjusting their behaviour to compensate for the reduced mechanical condition of their vehicles" [20, p. 569].

An examination of rear-end crashes [14] showed a regular pattern in which the probability that a car was struck in the rear, given that it was involved in a crash, declines systematically with car age. If a seven year old car was involved in a crash, the probability that it was struck from the rear is about 30% lower than the corresponding probability for new cars. Thus the findings of these two studies [14,20] suggest behavioral responses to cars being in

newer condition, with better braking likely the dominant factor. These results, together with the Munich taxicab result [6], suggest that drivers may be using the technical superiority of ABS to achieve benefits other than overall risk reduction. From a formal economic perspective, a technical innovation that the driver can choose to use in different ways is of higher value than one for which there is one prescribed use, such as safety (a ten dollar gift certificate valid only in a bookstore is of less value than ten dollars, which can be spent anywhere, including the bookstore).

There are many possible uses of a technological innovation like ABS beyond the reduction in overall crash risk. Anecdotally, we have heard drivers make comments like "I would not have gone out if I did not have ABS." If overall crash risk remains unaltered, but trips that would otherwise have been canceled are driven, then ABS has clearly provided an overall benefit even though overall crash risk has remained unchanged.

Various mechanisms can lead to ABS influencing driver behavior. Suppose a driver makes an emergency stop on a snow-covered road. If the driver is inexperienced on snow and is driving a non-ABS-equipped vehicle, a negative experience such as a skid or even, on much rarer occasions, a crash may result. Such feedback will encourage the driver to approach snow-covered roads with increased caution in the future. On the other hand, if the vehicle has ABS it is more likely to remain under control. Thus ABS drivers, regardless of their knowledge of ABS [26], will receive feedback that their driving was appropriate, and, according to one theory of driver behavior [27], will approach a similar situation in the future at a slightly higher speed.

At about the same time as the studies reported here were being performed, Kahane [28] was addressing the same questions. He used data from two (MO and PA) of the five states used here, plus Florida. He used calendar years 1990-1992 compared to our 1992-1993. He used 48 make-model subseries of 1985-1992 model year vehicles, compared to the seven 1991 and 1992 model year vehicles used here. There are many differences in detail, technique, approach, analysis and assumptions between the two studies. Overall the results are in remarkable agreement. For example, Kahane reports a statistically reliable 49% increase in rollover risk to be associated with ABS, compared to our finding of a  $(39 \pm 16)\%$  increase. The degree of agreement increases confidence that the effects reported are real changes in crash risk that are associated with ABS in general, and do not depend on the specific vehicles, states, years of data, or methods of analysis.

Additional information on the relationship between rollover risk and ABS is provided by Hertz et al. who report a significant increase in fatal rollover crashes to be associated with ABS for passenger cars [29], but a significant reduction in non-fatal rollover risk for light trucks with all-wheel ABS systems [30]. Lau and Padmanaban [10] also find ABS to be associated with increased rollover risk. Their study, which uses police reported crashes per registered vehicle, generally finds larger risk reductions to be associated with ABS than other studies; they report a 6% to 8% reduction on dry roads and a 17% to 19% reduction on wet roads. Farmer et al. [11] suggest these values may be related to possible limitations of [10], especially as such large differences would be expected to lead to reductions in insurance claims larger than is consistent with direct examinations of insurance claims [9].

## SUMMARY OF ABS EFFECTIVENESS STUDIES

The many different measures, methods, data sets, weather conditions, crash types, crash severities, etc. used in the studies discussed above makes it difficult to effectively synthesize all available findings. Tables 9-11 present the results in a format aimed at facilitating comparisons and supporting general conclusions.

For dry roads, only two of the entries in Table 9 indicate a statistically significant reduction in risk, compared to six indicating a risk increase. The general pattern in Table 9 suggests it is unlikely that on dry roads ABS can materially reduce risk.

The wet road results (Table 10) indicate a statistically significant decrease in risk for nine entries, compared to an increase for four, suggesting that ABS materially reduces risk on wet roads. ABS leads to a substantial reduction in the risk of crashing into a followed vehicle on wet roads, but with a corresponding increase in the risk of being struck by a following vehicle.

For all roadway conditions (Table 11), the first entry in the table indicates no observed difference in overall insurance claims to be associated with ABS [9]. If ABS reduces risk on wet roads, as the evidence supports, then no observable effect on total crash risk precludes the possibility that ABS is reducing risk on dry roads. The assumption used earlier of zero effect on dry roads thus seems to be a reasonable approximation.

A consistent finding in each of Tables 9-11 is that ABS is associated with increased rollover risk, and with increased

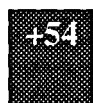
Table 9.

Summary of estimates in the cited studies<sup>①</sup> of the percent change in risk associated with ABS when driving on DRY roads. The interpretation of the first entry is that ABS is associated with a 54% increase in rollover risk.

## Results for DRY roads

Author [Ref.]	Measures	Data	ALL CRASHES (Single or multiple vehicle)							MULTI-VEHICLE CRASHES					
			Fatalities in ABS vehicle	All crash types		Rollover		Pedestrian bicycle, etc.		All		Striking lead vehicle		Struck by foll. veh.	
				Fatal <sup>②</sup>	All	Fatal	All	Fatal	All	Fatal	All	Fatal	All	Fatal	All
HLDI [9]	<u>Insurance claims</u> Insured vehicle	Insurance claims													
Evans [12]	<u>Risk one condition</u> Risk in another	MO,TX <sup>③</sup>													
Kahane [28]	<u>Relevant</u> Non-Relevant	FL,MO,PA FARS					+54			0	0	+5	+1		-1
Hertz et al. [29]	<u>Relevant</u> Non-Relevant	FL,MO,PA FARS				+54	+27						-9		
Evans and Gerrish [13]	<u>Relevant</u> Non-Relevant	IN,MO,NC PA,TX											+3		+3
Lau and Padmanaban [10]	<u>Crashes or fatalities</u> Registered vehicle	FL,PA,NC FARS, Polk			-7										
Farmer et al. [11]	<u>Fatal Crashes</u> Registered vehicle	FARS R.L. Polk	+23	+15		+65 <sup>④</sup>			+1	+5					
Evans This paper	<u>Risk one condition</u> Risk in another	IN,MO,NC PA,TX													

### KEY



←% change at top  
**Increase** in risk



**Decrease** in risk  
←% change at bottom



Nominal % increase at top  
Authors report *not-statistically significant* result.  
Nominal % decrease at bottom

① Studies are listed in order of public availability.

② A fatal crash is one in which anyone is killed.

③ Police reported crashes in states indicated by postal codes.

④ Analysis restricted to fatalities in rollover vehicle -- fatalities to those not in the rollover vehicle are rare.

Table 10

Summary of estimates in the cited studies<sup>①</sup> of the percent change in risk associated with ABS when driving on WET\* roads. The interpretation of the first entry is that ABS is associated with a 13% reduction in crash

## Results for WET\* roads

Author [Ref.]	Measures	Data	ALL CRASHES (Single or multiple vehicle)							MULTI-VEHICLE CRASHES					
			All crash types			Rollover		Pedestrian bicycle, etc.		All		Striking lead vehicle		Struck by foll. veh.	
			Fatalities in ABS vehicle	Fatal <sup>②</sup>	All	Fatal	All	Fatal	All	Fatal	All	Fatal	All	Fatal	All
HLDI [9]	<u>Insurance claims</u> Insured vehicle	Insurance claims													
Evans [12]	<u>Risk one condition</u> Risk in another	MO,TX <sup>③</sup>			-13										
Kahane [28]	<u>Relevant</u> Non-Relevant	FL,MO,PA FARS				+34				-14	-24		-39		+27
Hertz et al. [29]	<u>Relevant</u> Non-Relevant	FL,MO,PA FARS				+14	+94					-35	-35		
Evans and Gerrish [13]	<u>Relevant</u> Non-Relevant	IN,MO,NC PA,TX											-32		+30
Lau and Padmanaban [10]	<u>Crashes or fatalities</u> Registered vehicle	FL,PA,NC FARS, Polk			-18										
Farmer et al. [11]	<u>Fatal Crashes</u> Registered vehicle	FARS R.L. Polk	+40	+18		+53 <sup>④</sup>			-10	+13					
Evans This paper	<u>Risk one condition</u> Risk in another	IN,MO,NC PA,TX			-10										

### KEY

**+34** ← % change at top  
**Increase** in risk

**-13** **Decrease** in risk  
← % change at bottom

**+14** Nominal % increase at top  
Authors report *not-statistically significant* result.  
Nominal % decrease at bottom

\*Definitions vary between studies -- some include snow, ice, slick, and even gravel roads (expected to have unimportant effect because of its rarity)

① Studies are listed in order of public availability.

② A fatal crash is one in which anyone is killed.

③ Police reported crashes in states indicated by postal codes.

④ Analysis restricted to fatalities in rollover vehicle -- fatalities to those not in the rollover vehicle are rare.

Table 11.

Summary of estimates in the cited studies<sup>①</sup> of the percent change in risk associated with ABS when driving under any roadway conditions. The interpretation of the first non-zero entry is that ABS is associated with a 44% increase in rollover risk.

## Results for all roadway conditions combined

Author [Ref.]	Measures	Data	ALL CRASHES (Single or multiple vehicle)							MULTI-VEHICLE CRASHES					
			Fatalities in ABS vehicle	All crash types		Rollover		Pedestrian bicycle, etc.		All		Striking lead vehicle		Struck by foll. veh.	
				Fatal <sup>②</sup>	All	Fatal	All	Fatal	All	Fatal	All	Fatal	All	Fatal	All
HLDI [9]	<u>Insurance claims</u> Insured vehicle	Insurance claims			0										
Evans [12]	<u>Risk one condition</u> <u>Risk in another</u>	MO,TX <sup>③</sup>					+44		-34						
Kahane [28]	<u>Relevant</u> <u>Non-Relevant</u>	FL,MO,PA FARS		-2	-3	+40	+49	-27	+3		0				
Hertz et al. [29]	<u>Relevant</u> <u>Non-Relevant</u>	FL,MO,PA FARS				+60	+24		+3						
Evans and Gerrish [13]	<u>Relevant</u> <u>Non-Relevant</u>	IN,MO,NC PA,TX													
Lau and Padmanaban [10]	<u>Crashes or fatalities</u> <u>Registered vehicle</u>	FL,PA,NC FARS, Polk		0	-9.5	0	+11								
Farmer et al. [11]	<u>Fatal Crashes</u> <u>Registered vehicle</u>	FARS R.L. Polk	+26	+16		+63 <sup>④</sup>			-1	+7					
Evans This paper	<u>Risk one condition</u> <u>Risk in another</u>	IN,MO,NC PA,TX					+39		-22						

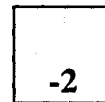
### KEY



←% change at top  
**Increase** in risk



**Decrease** in risk  
←% change at bottom



Nominal % increase at top  
Authors report *not-statistically significant* result.  
Nominal % decrease at bottom

<sup>①</sup> Studies are listed in order of public availability.

<sup>②</sup> A fatal crash is one in which anyone is killed.

<sup>③</sup> Police reported crashes in states indicated by postal codes.

<sup>④</sup> Analysis restricted to fatalities in rollover vehicle -- fatalities to those not in the rollover vehicle are rare.

involvement in some types of fatal crashes. Behavioral changes, particularly speed increases, may contribute to these effects.

Many studies, observations, and inferences indirectly support or suggest that ABS may be associated with higher average speeds. Taken together, all the available evidence renders inescapable the conclusion that overall average speeds increase somewhat as a result of the superior capabilities provided by ABS.

## ACKNOWLEDGMENTS

The Oregon data were provided through the kind help of Barney Jones of the Oregon Department of Transportation. Ken Strom of the Safety Research Department of GM R&D Center provided invaluable consultations in the analysis of this data. A number of productive interactions with Ian Lau are gratefully acknowledged. The tabulations from the state crash data files were provided by Peter Gerrish.

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# **THE CONTRIBUTION OF ONBOARD RECORDING SYSTEMS TO ROAD SAFETY AND ACCIDENT ANALYSIS**

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Paper Number 98-S2-O-34

## **ABSTRACT**

This paper presents onboard computer systems (black boxes), that

1. contribute to road safety by helping to reduce the number of accidents
2. provide data for accident analysis based on field experiences in USA and Europe with case studies.

There are several versions of onboard computers that record the performance of drivers and vehicles. Field experiences and case studies show that a 'feed back' of these records lead to a favourable modification of drivers' behaviour. Further these objective and accurate recordings allow detailed reconstruction and analysis of accidents.

## **FREQUENCY, COST AND CAUSE OF ACCIDENTS**

In the EU a total of 1.3 million road accidents with personal injury and 45.000 people killed were registered in 1995. The damage caused by these accidents has been estimated to reach as much as 45 billion ECU (about the same in US\$).

It is worth noting that - in Germany for instance - 90% of the registered accidents are caused by human error, only 10% by technical defects. These figures show that urgent action is required mainly in the field of driving behaviour.

## **EXPERIENCES GAINED WITH ONBOARD COMPUTERS FOR ACCIDENT RECONSTRUCTION AND ACCIDENT ANALYSIS**

Extensive experiences have been gained concerning the accident-preventing effect of onboard computers and their contribution to improved accident analysis. Let us mention the extraordinarily high contribution of the tachograph to improve road safety in the commercial vehicle sector in the European Union, which led many

other countries to also stipulate tachographs for the commercial transport of goods and passengers.

This paper describes the effect of two further onboard computers or black boxes. The first system is an onboard computer used in the first place to improve fleet management by recording such data as driving time, road speed, distance travelled, engine load etc. The second system is an Accident Data Recorder that has been developed to meet the specific requirements of accident analysis.

## **CASE STUDY FOR ACCIDENT PREVENTION BY A FLEET MANAGEMENT ONBOARD COMPUTER**

Laidlaw Inc., the largest contractor operator of school bus fleets in the United States fitted 50% of its Bridgeport fleet with onboard computers supplied by VDO North America. Based on a 6 months test two bus groups (with and without onboard computer) were analysed with the following results:

### **Reduction of Accidents**

Busses without VDO onboard computers accounted for 72% of accidents.

Bridgeport fleet would have suffered 62 accidents without the VDO onboard computers. The actual account was 43. Thus 19 accidents were prevented by the educative effect of the onboard computer.

### **Accident Data and Analysis Produce Legal Evidence**

Data extracted from vehicles involved in accidents allow detailed reconstruction and analysis. Conflicting reports from eye-witnesses, drivers, and passengers can be reconciled. The hard facts facilitate investigations considerably. Providing indisposed data on accidents can largely reduce the amount of management and administrative time required for review etc.

## Fleet Management Control Restored

The management is supplied with objective, accurate, minute-by-minute recordings of all drivers in monitored busses. Drivers with registered shortcomings can be counselled. These corrective interviews are the tool in the 'feedback loop' to the required modifications of drivers' behaviour and to restore fleet management control.

## Reduction of Liability and Maintenance Costs

By avoiding 19 accidents in the case study it could be estimated that 76.000 US\$ in body work expense was saved.

### Case study: Laidlaw Inc., Bridgeport, CT facility

1. Reduction of accidents
2. Accident data and analysis produce legal evidence
3. Fleet management control restored
4. Reduction of liability and maintenance costs

**Figure 1: Accident prevention by a fleet management onboard computer**

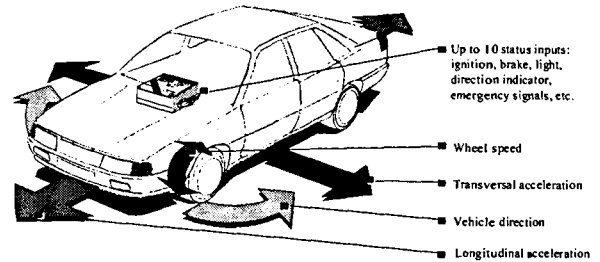
These results show that the investment is paid back twice. Firstly by reducing accidents with the involved human and social implications and costs and secondly, by the improvement of the fleet management.

## THE ACCIDENT DATA RECORDER

The Accident Data Recorder was specifically developed for accident analysis but has also proven its accident preventive character in more than four years of field experience.

### Technical Features of the Accident Data Recorder

Before discussing these two aspects, accident prevention and accident analysis, it will be useful to briefly explain the functions of the black box called Accident Data Recorder. This device will remind you of a flight recorder for use in passenger cars, trucks and busses.



**Figure 2: UDS system functions, sensors and status inputs**

The Accident Data Recorder is mainly composed of sensors measuring the transversal and longitudinal acceleration of the vehicle as well as its change of direction and road speed. The Accident Data Recorder discerns when and how long ignition, lamps, indicators and brakes have been activated. In case of an accident, this data is recorded with high precision 30 seconds before and 15 seconds after the accident. The Accident Data Recorder automatically detects the accident.

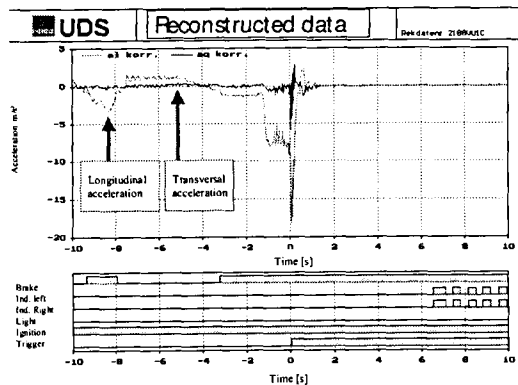
Up to three accidents can be stored in the Accident Data Recorder. Critical traffic situations can also be manually stored.

The Accident Data Recorder can easily be installed into any vehicle. There is no need for additional sensors.

## Accident Analysis and Accident Prevention

After this technical digression, it can be explained how the Accident Data Recorder contributes to optimising accident analyses and why it has an accident-preventing effect.

For the **accident analysis** expert, the Accident Data Recorder is an instrument, which provides objective accident data not available before. The analysis in view of accident reconstruction is made by a dedicated software package (see figure 3).



**Figure 3: Accident Reconstruction**

If an accident occurs, the Accident Data Recorder stores up to 500 times per second the relevant information such as longitudinal and transversal acceleration. With this accurate information it is possible to analyse at the computer even the slightest details of the critical fraction of a second (see Annex for an accident analysis case).

A study conducted by bast (Bundesanstalt für Strassenwesen = German Federal Road Agency), confirms the contribution of the Accident Data Recorder to improve accident analysis:

The bast study of June 1997 is based on information gathered from 42 real accidents in which vehicles fitted with the Accident Data Recorder were involved. This shows that the Accident Data Recorder increases the degree of certainty to as much as 100% compared to traditional sources of information both in the pre-crash phase and in all other phases of the accident in respect of individual characteristics which, normally, cannot be fully ascertained without the Accident Data Recorder. These include driver reaction, road speed characteristics over a period of the last 30 seconds preceding the crash or the sequence in case of mass rear-end collisions. Information on vehicle deceleration and vehicle speed where no marks can be found on the road as well as the accurate chronological correlation of the actuation of vehicle controls can be safely established.

With regard to **accident prevention** experience gained with the Accident Data Recorder during the last four years became evident that it considerably influences the driving behaviour and thus contributes to accident prevention.

In a number of vehicle fleets the accident rate and damages incurred could be reduced by up to 30%. How can this achievement be explained? It is the knowledge

about the fact that the driving behaviour can be checked objectively at any time which makes the driver to behave more attentively in critical accident-bound situations.

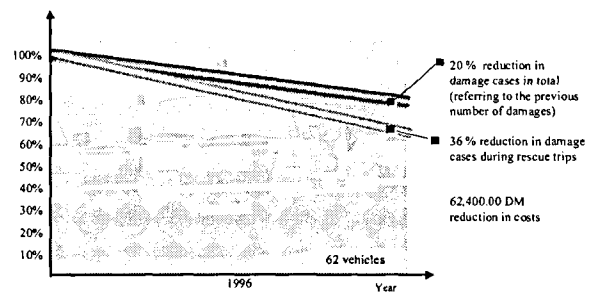
More careful driving will also cause less wear of material. The Accident Data Recorder can thus directly improve the running costs of a fleet company.

Out of the numerous series of preventive experience a few examples are shown below:

### Police of Berlin

Fitting all 62 squad cars of a Berlin police head office in 1996 reduced the number of accidents due to the driver's own fault by 20% and by 36% in emergency-trips. The cost involved could be reduced by approx. 25%.

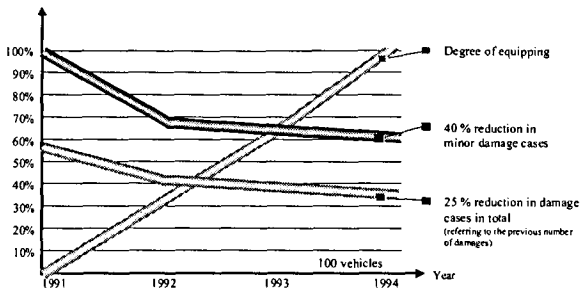
These positive results induced the Berlin police authority to equip all their squad cars - these are more than 400 vehicles - with the Accident Data Recorder.



**Figure 4: Example - Police of Berlin**

### WKD Pinkerton Security GmbH

In this company for property protection all passenger cars (approx. 100) that are used with a changing crew are fitted with Accident Data Recorders. This led the drivers to drive more carefully, adapting their driving behaviour to the individual traffic situation, with the result that the number of accidents decreased by 30%, minor damages even by 60%. This in turn led to considerable savings of insurance premiums.



**Figure 5: Example - WKD Pinkerton Security, Bisingen, Germany**

### **WBO (Association of Baden-Württemberg Bus Operators)**

In the pilot run promoted by the Baden-Württemberg Ministry of Transport with the Accident Data Recorder installed in busses run by WBO 123 Accident Data Recorders were involved. With the busses fitted with an Accident Data Recorder the number of accidents decreased between 15 and 20% compared with the reference period, depending of the company concerned.

### **Samovar**

In Great-Britain, the Netherlands and Belgium nine vehicle fleets with a total of 341 vehicles fitted with data recording equipment participated in the research program SAMOVAR (Safety Assessment Monitoring on Vehicles with Automatic Recording) conducted by the European Union in the framework of the Drive Project V 2007.

Together with a control panel involved in similar tests a total of 850 vehicles participated in the program. The data were collected over a period of 12 months. The result shows that the accident rate decreased by 28.1% by the use of the vehicle data recorder.

The Samovar Report finally concluded that the intelligent use of a vehicle data recorder is able to make a considerable, distinctive, and independent benefit to road traffic safety.

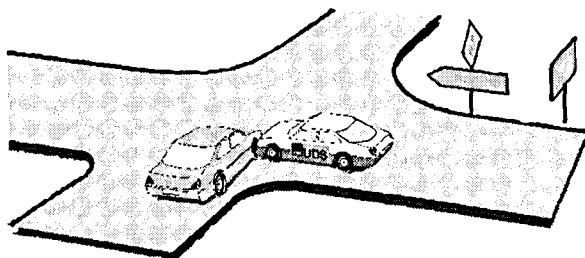
### **REQUESTS TO THE TRAFFIC POLICY**

Onboard computers and specially the Accident Data Recorder have been designed as a contribution to road safety and legal certainty. The experiences at hand show that the systems can come up with the expectations placed

in them. In view of the accident rates on our roads and the resulting human and economic damage we should make traffic policy aware of the opportunities of improving traffic safety conditions by means of vehicle data recording devices. It is also a question, which we have to find an answer for, whether we can accept a considerable lack of justice for traffic victims if modern technology offers relief.

## ANNEX

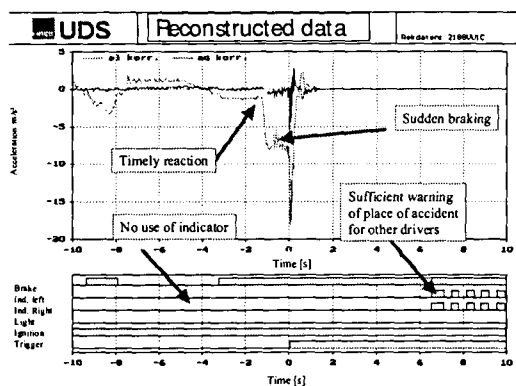
### Example of a Real Accident Analysis Intersection Accident



**Figure 1: The accident situation**

The picture shows a rather clear situation because of the priority-regulation on this junction. But the driver coming from the left accused the driver with the Accident Data Recorder of

- having entered the crossing at a too high speed
- having set the direction indicator to the right and thus causing him to enter the junction
- having shown no reaction to avoid the accident.



**Figure 2: Reconstructed data**

Figure 2 shows the raw data and proves at a glance that the driver coming from the right is not responsible for the accident. He reacted in time (braking) and didn't use the indicator.

As information for the accident analyst: At the point of the accident, the relevant data is stored with 500 Hertz, which means 500 times acceleration data and other information per second. This is very helpful in cases of more complicated accident situations.

# DRIVING SIMULATOR EXPERIMENT ON DRIVERS' BEHAVIOR AND EFFECTIVENESS OF DANGER WARNING AGAINST EMERGENCY BRAKING OF LEADING VEHICLE

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## ABSTRACT

The purposes of this research are the followings: one is to investigate drivers' behavior and characteristics against the emergency braking of the leading vehicle by the JARI driving simulator. The other is to clarify the effectiveness of danger warning of the leading vehicle. For this analysis, the experiment using the JARI driving simulator was conducted. The virtual leading car on the simulator is controlled automatically and rapidly stops by the trigger command of a simulator operator. The subjects are 14 males in 20 to 29 ages.

From the experimental data, the difference of such variables to be analyzed as brake delay time, mean deceleration and minimum headway distance were compared between in case that the drivers cannot predict the emergency braking and in the case that they can predict it. As a result, those parameters in the unpredictable situation were larger than in the predictable situation.

In order to improve the driver's avoidance characteristics, effectiveness of danger warning against the emergency braking of the leading car was examined. The main effect and the interaction of the vehicle velocity, the warning time and the headway time on the variables to be analyzed were clarified by analysis of variance. The result of this test showed that the effect of the danger warning was recognized and the danger warning can make compensation for the increase of the brake delay time in the unpredictable situation.

## INTRODUCTION

An advanced vehicle that installs some ITS systems warns a driver to avoid an obstacle detected automatically and/or starts automatic avoidance operations such as automatic braking and automatic steering. In a transitional period of the spread of the advanced vehicle, there is a traffic in which the advanced vehicle and an ordinary vehicle are intermixed. A driver getting on the ordinary car still perceives an obstacle manually to avoid it.

When the leading advanced vehicle quickly avoids an obstacle on the assumption that the ordinary car follows the leading vehicle, a driver getting on the ordinary car possibly behaves unsafely because of the leading vehicle movement contrary to his or her expectation. Besides, the ordinary

car might disturb an advanced function of the advanced vehicle. For example, in case of the ordinary vehicle forces its way into the advanced vehicles, an automatic avoidance operation of the advanced vehicle may quite often function. Moreover, it is not found whether a driver who usually gets on the ordinary vehicle can adapt to the advanced vehicle or not, and vice versa. These are important problems in human factors area of ITS to promote the spread of its technologies.

The purposes of this research are the followings: one is to investigate drivers' behavior and characteristics against the emergency braking of the leading vehicle. The other is to clarify, the effectiveness of danger warning of the leading vehicle. Experiment using the JARI driving simulator is conducted.

## HEADWAY DISTANCE IN ACTUAL VEHICLE

### Test Method

Headway distance of each subject is measured by a laser radar installed in an actual vehicle on the JARI test course. The result is used for determining the initial headway distance defined next chapter.

The subjects (14 males in their twenties) drove the own vehicle to follow the leading vehicle an experimenter operated. The subjects were instructed to keep constant headway distance with consciousness of their ordinary driving. The speed of the leading vehicle was 60km/h. The subjective estimation of the headway distance was also recorded simultaneously.

### Result

Comparison between headway distance measured by laser radar and by subjective estimation is shown in Figure 1. When the plotted points are on the 45 degrees line, the subjective estimation coincides with data measured by laser radar. According to Figure 1, most of the drivers estimate the headway distance to be less than the actual distance.

This result is utilized for checking initial conditions in simulator experiment against actual driving situations.

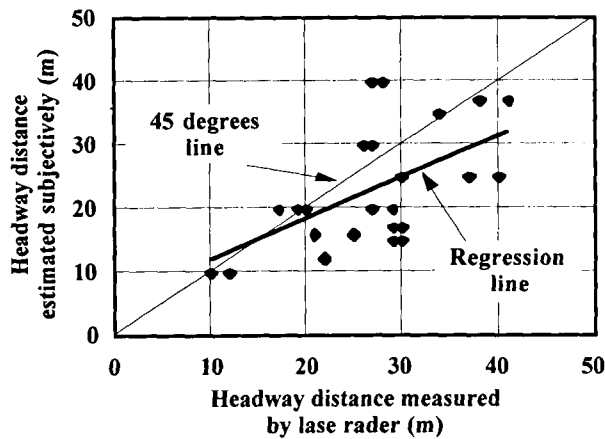


Figure 1. Headway distance of ordinary driving.

## DRIVERS' BEHAVIOR AGAINST EMERGENCY BRAKING OF LEADING VEHICLE

### Test Method using the Driving Simulator

Drivers' behavior against emergency braking of the leading vehicle was investigated in this test using the JARI driving simulator[1] to avoid real collision to the leading vehicle. As the computer graphics of the driving simulator creates the virtual leading vehicle, the subjects drives the car simulated by the driving simulator to follow the leading vehicle.

When the leading vehicle is about to stop, the subjects are allowed to operate steering and/or braking. The leading vehicle, however, turns left or right in accordance with a driver's steering action. Thus, unless the driver puts on the brake, the following vehicle that the driver operates necessarily collides with the leading vehicle. We did not inform the subjects of this matter.

Driving conditions in the driving simulator must be set for the actual situations in order to adjust experimental results to that by a real vehicle. In this test the headway distance measured by laser radar (chapter 2) was defined as the reference distance. We let the subjects keep the similar headway distance to the reference distance on the driving simulator.

The tasks and their scenarios are shown in Table 1.

Table 1.  
Tasks in Experiment

Task #	Velocity (km/h)	Deceleration ( $m/s^2$ )	Situation
1	60	0	Exercises
2	60	5	Unpredictable
3	60	5	Predictable
4	100	3	Predictable

The task #1 is exercise and impresses nothing of the rapid braking of the leading vehicle on the subjects, in order to perform the next task #2 successfully. The task #2 is a so-called surprise test in which the leading vehicle stops rapidly without prediction of the subjects. The headway distance before braking is set to the reference distance.

In the task #3 and #4 the subjects already knew the emergency braking of the leading vehicle. The emergency braking of the leading vehicle was put on at a random point of place every trial. The initial velocity and the deceleration of the leading vehicle were varied shown in Table 1. The subjects were allowed to try it twice every task. In the first trial the headway distance was set to the reference distance. In the second trial the headway distance was set to different distance according to the result of the first trial, i.e., if the collision occurred, the headway distance was longer than the reference distance; if it did not, the headway distance was shorter than the reference distance.

The leading vehicle is accelerated to the speed of 60 or 100km/h after the start, and keeps constant. At a certain place the step signal of deceleration is given to the leading vehicle (Figure 2). Simultaneously the stop lamps are turned on and the pitching angle of the leading vehicle is varied in proportion to the deceleration. If the own vehicle collides with the leading vehicle, the subjects can know the collision by blinking red light on the screen and the collision sound instead of the shock.

### Definition of Variables to be Analyzed

The variables to be analyzed are defined as follows:

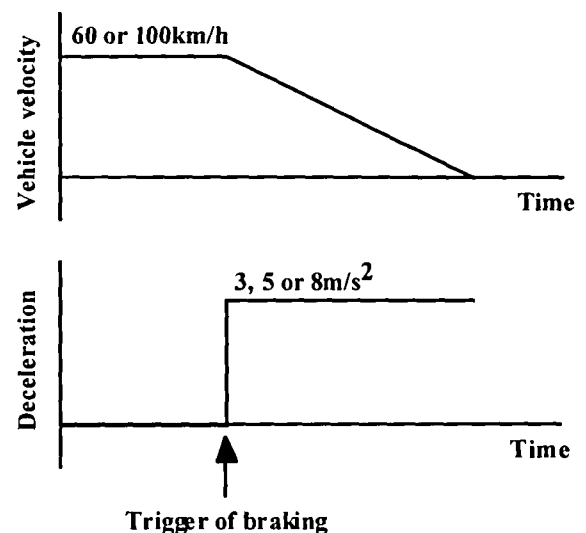


Figure 2. Pattern of deceleration of the leading vehicle.



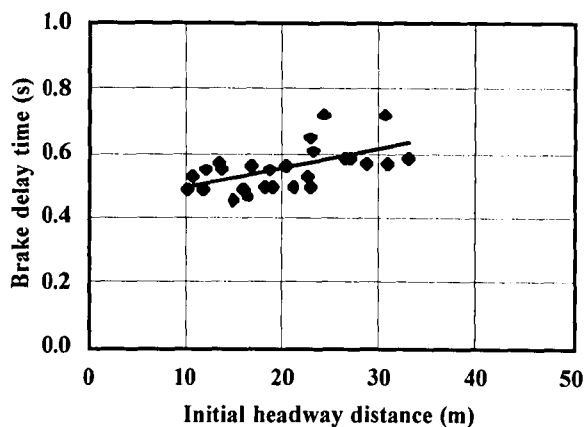


Figure 3. Relation between brake delay time and initial headway distance at 60km/h and  $5\text{m/s}^2$ .

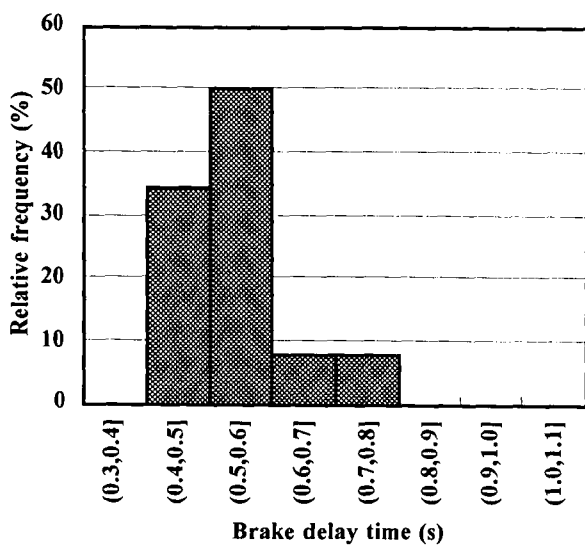


Figure 4. Relative frequency distribution of brake delay time.

- (1) *Initial headway distance*: it is a mean headway distance during 2seconds before the trigger of the emergency braking.
- (2) *Minimum headway distance*: it is a headway distance when the own vehicle approaches the closest to the leading vehicle after the trigger of the emergency braking.
- (3) *Brake delay time*: it is a time from the trigger of the emergency braking to the start of brake pedal operation of the subjects.
- (4) *Mean deceleration*: it is an arithmetical mean of the own vehicle deceleration from the trigger of the emergency braking to the moment of the minimum headway distance.

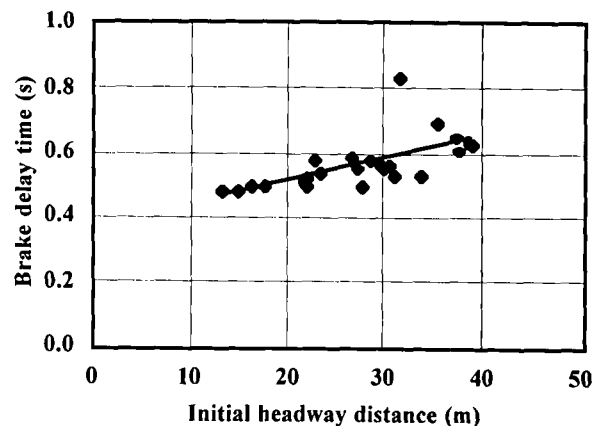


Figure 5. Relation between brake delay time and initial headway distance at 100km/h and  $3\text{m/s}^2$ .

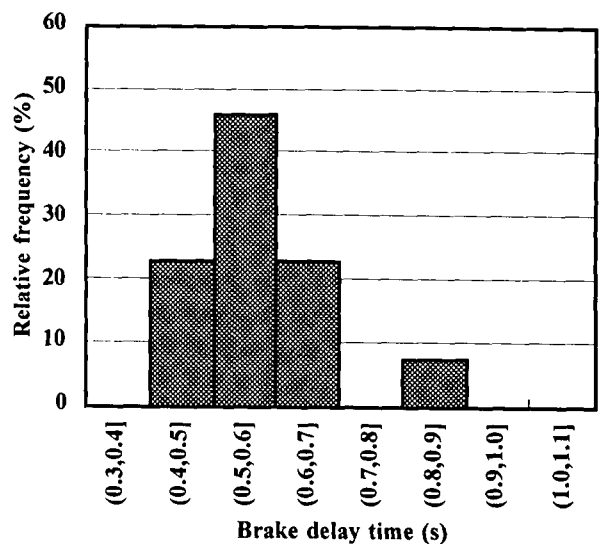


Figure 6. Relative frequency distribution of brake delay time at 100km/h &  $3\text{m/s}^2$ .

### Results in Predictable Situations

The results of task #3 and #4 are shown here.

**Brake delay time** - Figure 3 shows the relation between brake delay time and initial headway distance at the velocity of 60km/h and the deceleration of  $5\text{m/s}^2$  (task #3). The brake delay time slightly increases with the initial headway distance. Figure 4 is relative frequency distribution of the brake delay time. The ratio of (0.5s, 0.6s] is about 50%, and the ratio of (0.4s, 0.6s] occupies approximately 85%, where "(" means "more than" and "]" means "less than or equal to".

Figure 5 shows the relation between brake delay time and initial headway distance at the velocity of 100km/h and the deceleration of  $3\text{m/s}^2$  (task #4). The brake delay time

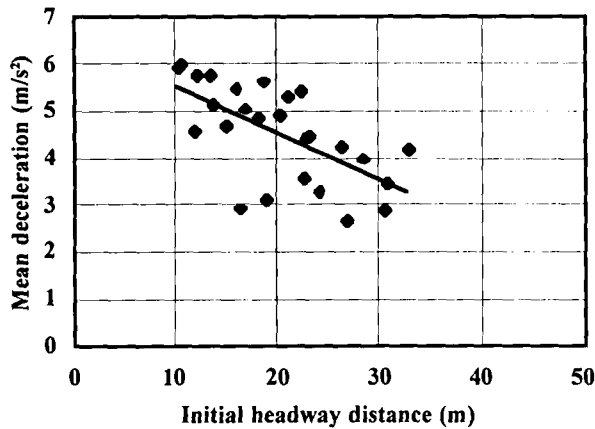


Figure 7. Relation between mean deceleration and initial headway distance at 60km/h and 5m/s<sup>2</sup>.

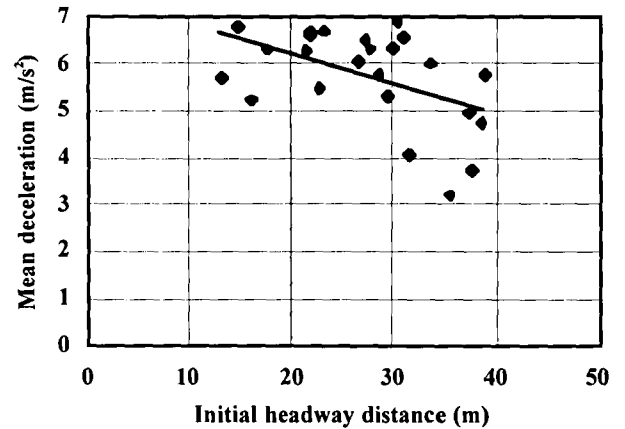


Figure 9. Relation between mean deceleration and initial headway distance at 100km/h and 3m/s<sup>2</sup>.

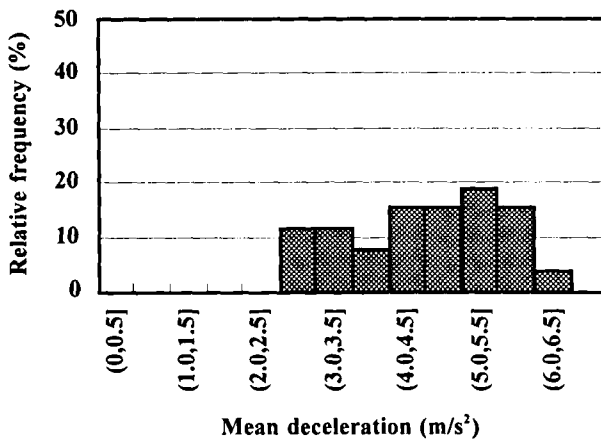


Figure 8. Relative frequency distribution of mean deceleration at 60km/h and 5m/s<sup>2</sup>.

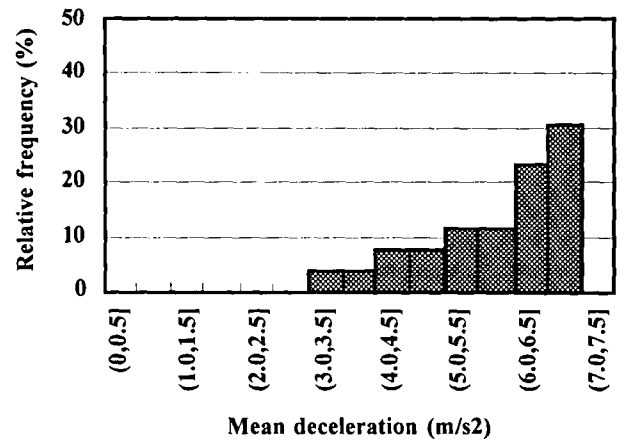


Figure 10. Relative frequency distribution of mean deceleration at 100km/h and 3m/s<sup>2</sup>.

becomes a little smaller than the previous result. Figure 6 is also relative frequency distribution of the brake delay time. The brake delay time at peak ratio is the same as the previous result.

**Mean deceleration** - Figure 7 shows the relation between mean deceleration and initial headway distance at the velocity of 60 km/h and the deceleration of 5m/s<sup>2</sup> (task #3). The mean deceleration decreases with the increase of the initial headway distance. Figure 8 is relative frequency distribution of the mean deceleration. Although the peak is at (5.0m/s<sup>2</sup>, 5.5m/s<sup>2</sup>], it is widely distributed from 2.5m/s<sup>2</sup> to 6.5m/s<sup>2</sup>.

Figure 9 shows the similar relation at the velocity of 100km/h and the deceleration of 3m/s<sup>2</sup> (task #4). The mean deceleration is larger than that in the result of 60km/h. This tendency is represented by the distribution in Figure 10. The peak is at (6.5m/s<sup>2</sup>, 7.0m/s<sup>2</sup>], and its ratio occupies about 30%.

**Minimum headway distance** - Figure 11 shows the relation between minimum headway distance and initial headway distance at the velocity of 60km/h and the deceleration of 5m/s<sup>2</sup> (task #3), where the minimum headway distance less than or equal to 0 m means the rear-end collision. In figure 11 the regression curve of the minimum headway distance decreases with reduction of the initial headway distance. This curve reveals that the rear-end collision occurs less than about 10m of the initial headway distance (this boundary of initial headway distance is defined as critical headway distance).

Figure 12 shows the similar result at the velocity of 100km/h and the deceleration of 3m/s<sup>2</sup> (task #4). The critical headway distance is about 17m; i.e., the collision occurs less than about 17m of initial headway distance.

### Results in Unpredictable Situation

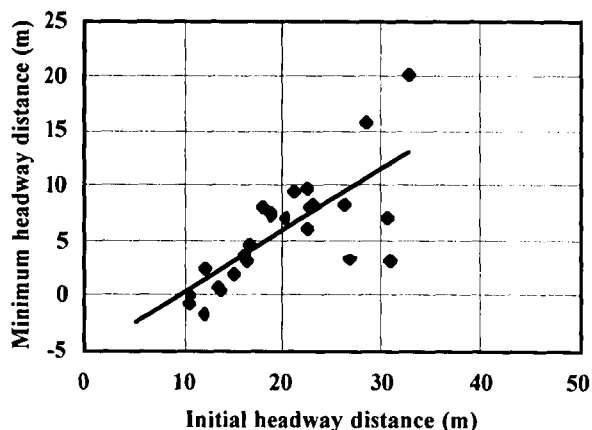


Figure 11. Relation between minimum headway distance and initial headway distance at 60km/h and  $5\text{m/s}^2$ .

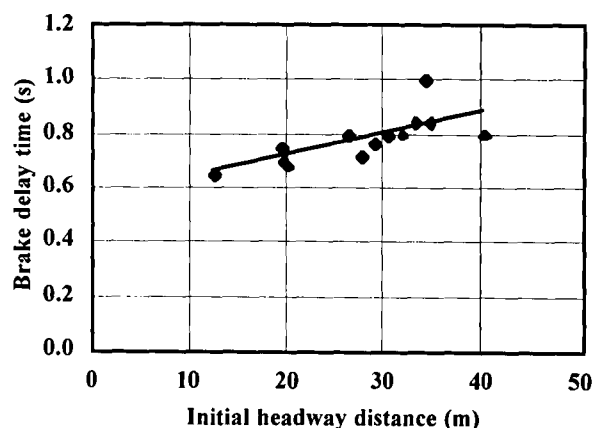


Figure 13. Relation between brake delay time and initial headway distance at 60km/h and  $5\text{m/s}^2$  in unpredictable situation.

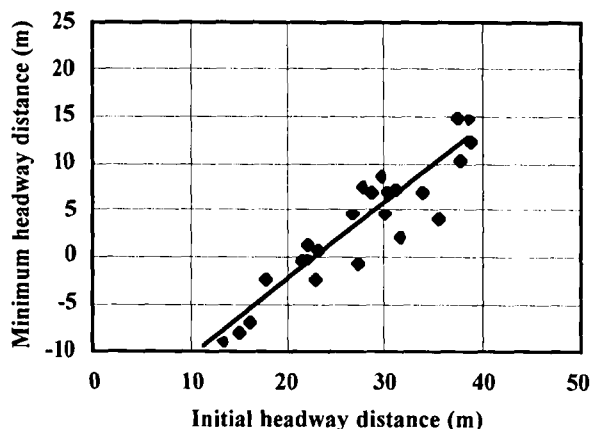


Figure 12. Relation between minimum headway distance and initial headway distance at 100km/h and  $3\text{m/s}^2$ .

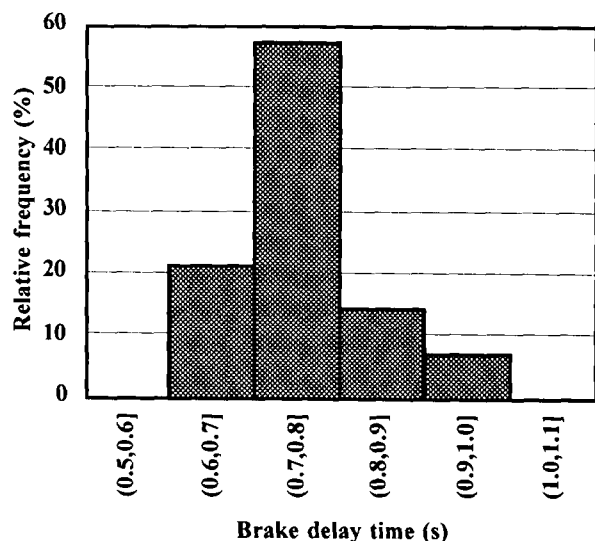


Figure 14. Relative frequency distribution of brake delay time in unpredictable situation.

The results of the task #2 in which the emergency braking put on the leading vehicle without prediction of the subjects are shown in this section. The experimental conditions are the same as the task #3 except the unpredictable situation.

**Brake delay time** - Figure 13 shows that the relation between brake delay time and the initial headway time. The increase tendency in the relation is similar to the predictable situation, task #3. The relative frequency distribution is shown in Figure 14. As the ratio of (0.7s, 0.8s] is about 55%, the brake delay time is about 0.2s larger than the predictable situation.

**Mean deceleration** - Figure 15 shows that the relation between the mean deceleration and the initial headway distance. The mean deceleration decreases with the increase of the initial headway distance as well as that of the predictable situation. The relative frequency distribution is, however, different from that in the predictable situation because Figure

16 reveals that the peak is at  $(1.5\text{m/s}^2, 2.0\text{m/s}^2]$  and the distribution range is narrower than that in the task #3.

**Minimum headway distance** - Figure 17 shows that the relation between minimum headway distance and the initial headway distance. The regressive curve in Figure 17 reveals that the critical headway distance is about 15m. This value is larger than the predictable situation in spite of the fact that the experimental conditions are the same except predictable or unpredictable. In addition to this, although the minimum headway distances at the initial headway distance of 20m and 30m are about 6m and 11m respectively in the predictable situation, task #3, those are about 3m and 8m respectively in the unpredictable situation, task #2.

**Comparison between the predictable situation and the unpredictable situation** - Thus, the following results

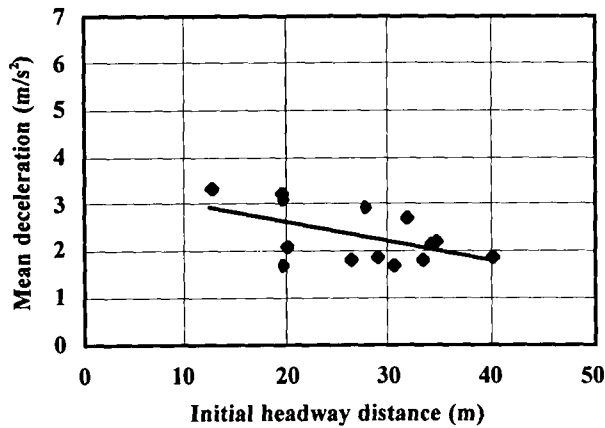


Figure 15. Relation between mean deceleration and initial headway distance at 60km/h and 5m/s<sup>2</sup> in unpredictable situation.

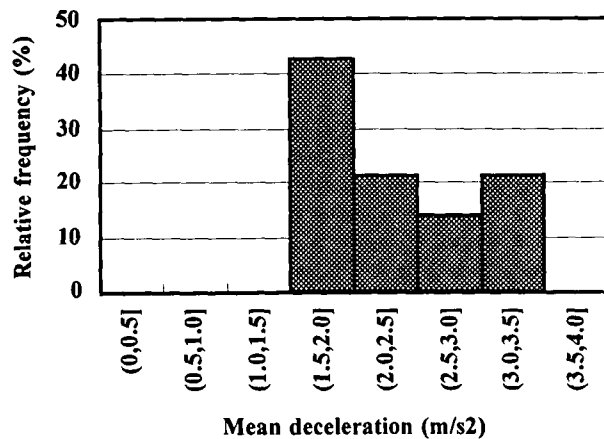


Figure 16. Relative frequency distribution of mean deceleration in unpredictable situation.

are obtained: in the unpredictable situation in comparison with the predictable situation,

- (1) the brake delay time is about 0.2s larger,
- (2) the mean deceleration is about 4m/s<sup>2</sup> smaller,
- (3) the critical headway distance is about 5m larger.

Therefore, possibility of the collision becomes high if a leading vehicle rapidly decelerates when an own car follows with short headway distance without anticipation of a driver. One of the improvements is an assist from the leading vehicle with danger warning. Next chapter the effectiveness of the danger warning is examined.

## EFFECTIVENESS OF DANGER WARNING AGAINST EMERGENCY BRAKING

### Method of Danger Warning

In order to clarify the effectiveness of the danger warn-

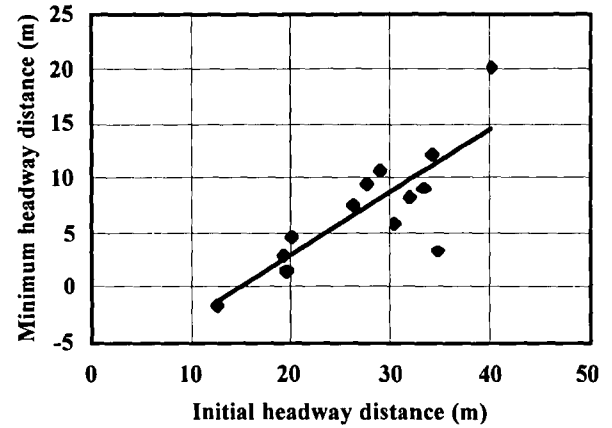


Figure 17. Relation between minimum headway distance and initial headway distance at 60km/h and 5m/s<sup>2</sup> in unpredictable situation.

ing, the following experiment was conducted. When the subject starts the own vehicle, the leading vehicle starts at the same time. The leading vehicle automatically keeps the headway time (headway distance / vehicle velocity) to be 0.7s or 1.0s. The subject controls the speed to be 60 or 100km/h, and the leading vehicle runs at the same speed. The deceleration of the leading vehicle after the braking trigger is the step of 8m/s<sup>2</sup>. The trigger point of place was set randomly every trial.

The danger warning was generated using the stop lamps of the leading vehicle. They were lighted up 0.3s before the trigger of the braking. This time is defined as the warning time. The subjects can know the emergency braking of the leading vehicle before the trigger.

The tasks are from task A to J shown in Table 2. The order of the tasks of each subject was changed to eliminate the order effect. Analysis of variance is performed using the data of this experiment.

Table 2.  
Tasks in Experiment with Danger Warning

Task	Velocity (km/h)	Deceleration (m/s <sup>2</sup> )	Headway time (s)	Warning time (s)
A	60	8	0.7	0.0
B	60	8	0.7	0.3
C	60	8	1.0	0.0
D	60	8	1.0	0.3
E	100	8	0.7	0.0
F	100	8	0.7	0.3
G	100	8	1.0	0.0
H	100	8	1.0	0.3
I	100	8	0.5	0.0
J	100	8	0.5	0.3

Table 3.  
Result of Analysis of Variance in Brake Delay Time

	SS	df	MS	F
A: Velocity	0.034	1	0.034	1.99
B: Warning time	1.922	1	1.922	112.89 **
C: Headway time	0.015	1	0.015	0.90
A x B	0.00026	1	0.000	0.02
B x C	0.0056	1	0.006	0.33
A x B	0.0261	1	0.026	1.53
A x B x C	0.0017	1	0.002	0.10
e	1.770	104	0.017	

Significant level: \*\*<0.01 \*<0.05

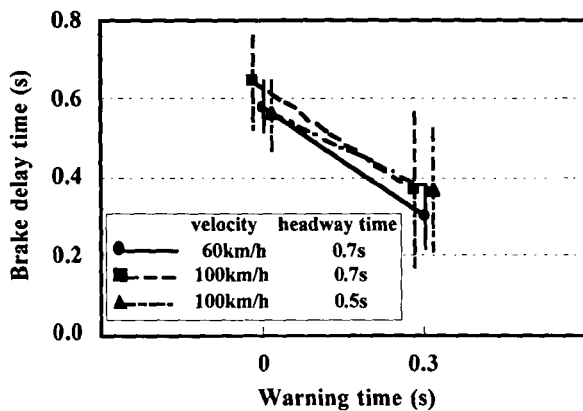


Figure 18. Relation between brake delay time and warning time (average and standart deviation).

### Effectiveness of Danger Warning

**Brake Delay Time** - The result of analysis of variance is shown in Table 3. Only the main effect of the warning time has significant difference.

Figure 18 shows the relation between the brake delay time and the warning time with the vehicle velocity and the headway time as parameters. The brake delay time becomes short when the warning time is 0.3s (the stop lamps light up 0.3s before the trigger of the braking). The decrease of the brake delay time is about 0.25s. It is almost equal to both the warning time and the difference between the brake delay time in predictable situation and in the unpredictable situation mentioned in the previous chapter. Thus, at least about 0.3s is required of the warning time.

**Mean Deceleration** - The result of analysis of variance is shown in Table 4. The main effect of the vehicle velocity and the warning time have significant difference. The former and the latter significant level are 1% and 5% respectively. The interaction is not detected as well as the result of the brake delay time.

Table 4.  
Result of Analysis of Variance in Mean Deceleration

	SS	df	MS	F
A: Velocity	15.276	1	15.276	94.358 **
B: Warning time	0.694	1	0.694	4.285 *
C: Headway time	0.305	1	0.305	1.882
A x B	0.027	1	0.027	0.165
B x C	0.272	1	0.272	1.681
A x C	0.352	1	0.352	2.175
A x B x C	0.001	1	0.001	0.005
e	16.837	104	0.162	

Significant level: \*\*<0.01 \*<0.05

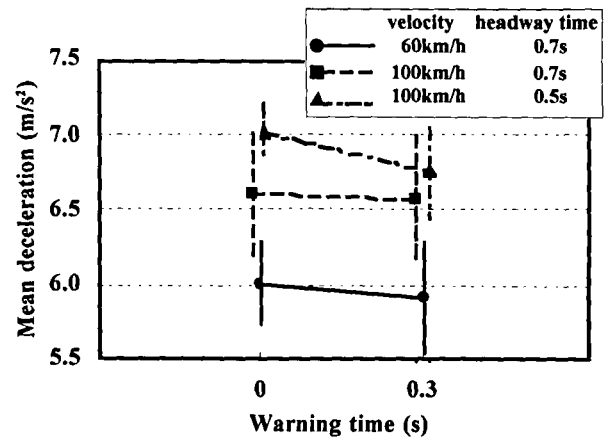


Figure 19. Relation between mean deceleration and warning time (avelage and standart deviation).

Figure 19 shows the relation between the mean deceleration and the warning time with the vehicle velocity and the headway time as parameters. Although the significant difference of the warning time is detected in Table 4, the effect of the warning time is recognized only at the vehicle velocity of 100km/h and the headway time of 0.5s in Figure 19. The warning time has almost no effect on the mean deceleration.

**Minimum Headway Distance** - The result of analysis of variance is shown in Table 5. The main effect of all the variables: the vehicle velocity, the warning time and the headway time have significant difference. And then, the interaction between the vehicle velocity and the headway distance is detected with 5% of the significant level.

Figure 20 shows the relation between the minimum headway distance and the warning time with the vehicle velocity and the headway time as parameters. When the warning time is 0.3s, the minimum headway distance becomes larger. The collision occurs only at the vehicle velocity of 100km/h and the headway time of 0.5s in this warning time.

The increase in the minimum headway distance is

**Table 5** Result of analysis of variance in minimum headway distance

	SS	df	MS	F
A: Velocity	407.12	1	407.12	15.842 **
B: Warning time	957.68	1	957.68	37.266 **
C: Headway time	969.64	1	969.64	37.732 **
A x B	83.52	1	83.52	3.250
B x C	16.59	1	16.59	0.646
A x C	169.78	1	169.78	6.607 *
A x B x C	2.07	1	2.07	0.081
e	2672.63	104	25.69	

Significant level: \*\*<0.01 \*<0.05

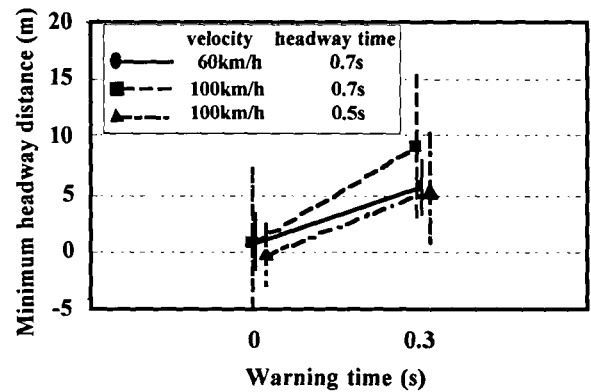
shown in Table 6. The increase at the headway distance of 0.7s is equal to the distance covered during the warning time of 0.3s. The increase is, however, less than "the warning time multiplied by the vehicle velocity" at the vehicle velocity of 100km/h and the headway time of 0.5s. Thus, in case the headway distance is relatively large, the minimum headway distance can be expanded to the distance added "the warning time multiplied by the vehicle velocity" by the

**Table 6.**  
Increase of Minimum Headway Distance by Danger Warning

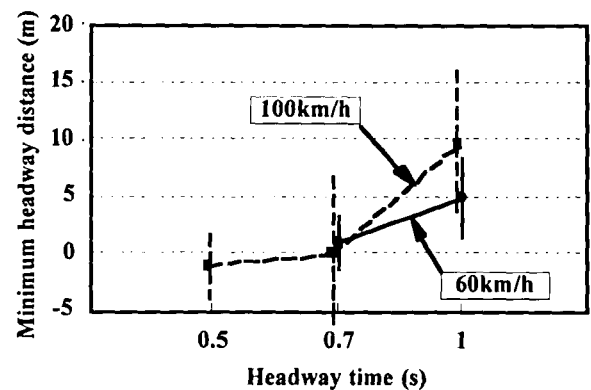
Conditions		Minimum headway distance (m)		Increase of minimum headway distance (m)	Velocity multiplied by warning time (m)
Velocity (km/h)	Headway time (s)	at warning time 0.0s	at warning time 0.3s		
60	0.7	1.02	5.64	4.62	5.00
100	0.7	0.37	8.99	8.62	8.33
100	0.5	-0.72	4.94	5.67	8.33

danger warning. And then, the shorter the headway time, the harder the increase of the minimum headway distance.

The relation between the headway time and the minimum headway distance with the vehicle velocity as a parameter is shown in Figure 21, because there is the interaction between vehicle velocity and the headway time. Although the average at 60km/h is a little larger than that at 100km/h at the headway time of 0.7s, the average at 100km/h is much larger than that at 60km/h at the headway time of 1.0s. There is much difference of the minimum headway distance to variation of the vehicle velocity in case of large headway time.



**Figure 20.** Relation between minimum headway distance and warning time (average and standard deviation).



**Figure 21.** Interaction between vehicle velocity and headway time (average and standard deviation)

## CONCLUSIONS

In this research drivers' behavior and characteristics against the emergency braking of the leading vehicle was investigated using the JARI driving simulator. Besides, the effectiveness of danger warning of the leading vehicle was clarified. The following results were obtained:

- (1) In the unpredictable situation the brake delay time and the critical headway distance are about 0.2s and 5m larger respectively, and the mean deceleration is  $4\text{m/s}^2$  smaller than in the predictable situation.
- (2) The main effect having the significant difference are (a) the warning time on the brake delay time, (b) the vehicle velocity and the warning time on the mean deceleration, and (c) the vehicle velocity, the warning time and the headway time on the minimum headway distance. There is also the interaction between the vehicle velocity and the headway time on the minimum headway distance.
- (3) The effect of the danger warning is recognized. In case the headway distance is relatively large, the minimum headway distance can be expanded to the distance added "the warning time multiplied by the vehicle velocity" by the danger warning. Thus, the danger warning can make compensation for the increase of the brake delay time in the unpredictable situation. However, at least about 0.3s is required of the warning time.

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# ENHANCEMENT OF VEHICLE STABILITY BY CONTROLLING THE FRONT BRAKES AND ENGINE TORQUE

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Paper Number 98-S2-P-14

## ABSTRACT

For the progress of vehicle safety, enhancement of active safety performance is as important as crash safety performance.

In emergency situations, it is very difficult for an ordinary driver to stabilize the vehicle because steering, braking, and/or other operations in this situation change the vehicle behavior suddenly.

From this point of view, enhancement of vehicle stability is very important for active safety. HONDA has developed an active safety system called VSA (Vehicle Stability Assist) based on expanding the usual active safety system, ABS (Anti-lock Brake System) and TCS (Traction Control System).

VSA controls front wheel brakes and engine torque to stabilize the vehicle by comparing yaw rate of the vehicle with the reference value calculated from lateral acceleration and vehicle speed, and the driver's intention estimated from steering angle.

## INTRODUCTION

In a broad sense, active safety performance is related to all aspects of vehicle performance in terms of improving vehicle safety. Vehicle motion stability in particular is said to be closely associated with active safety from the perspective of accident avoidance.

Chaotic vehicle behavior caused by environmental, vehicle and human factors makes it difficult for an ordinary driver to control the vehicle. This is particularly evident when operating a vehicle under tense circumstances such as when attempting to avoid an accident.

For example, there are numerous cases where accidents could not be prevented because sudden steering, braking, and/or other evasive actions changed the vehicle behavior abruptly, making it impossible to steer the vehicle. From this point of view, there are hopes for new driving assistance technology to support driver operations from the vehicle side during critical behavior.

HONDA feels that it is extremely important in terms of active safety to have the vehicle detect when behavior becomes unstable due to evasive actions or sudden changes in the environment, etc., and to suppress any resulting changes in behavior. This thinking has led to the

development of an original VSA (Vehicle Stability Assist) system based on expanding the conventional ABS (Anti-lock Brake System) and TCS (Traction Control System). This VSA system suppresses vehicle sliding at all times even when not braking or accelerating to ensure that drivers are able to control the vehicle.

This paper describes the concept, principle, system configuration, control outline and effects of the VSA system. In addition, an original tire model is also introduced in the section concerning the principles of VSA.

## BACKGROUND

Recently, typical active safety devices such as ABS and TCS are becoming standard equipment. However, both FaAA (Failure Analysis Associates INC.) and NHTSA have reported that "while the installation of ABS has reduced the number of multiple-car accidents in the U.S., single-car accidents have on the contrary increased." This is thought to be largely due to a lack of understanding on the part of the driver and insufficient PR by the manufacturer, thus giving the driver the false impression that ABS makes it possible to exceed physical limits and making the driver overconfident and reckless. However, there are also other causes, and these reports suggest that there is still some room for improvement in these systems.

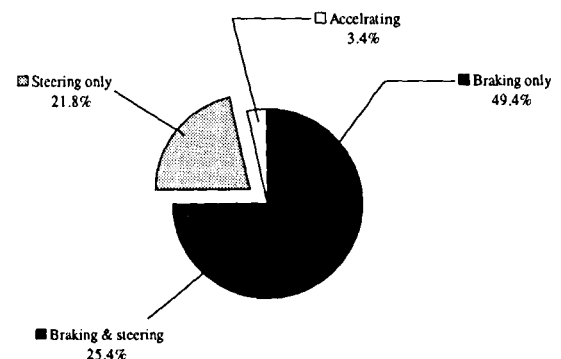


Figure 1. Pre-accident evasive operation(s) (2673 cases)



The **ABS** and **TCS** systems suppress peripheral slipping of the tires during critical braking and accelerating, thus ensuring sufficient tire lateral force. In other words, these driving assistance systems increase the driving margin with respect to lateral vehicle motion during critical braking and accelerating. However, these systems are essentially limited in that:

"They do not function when the driver is not stepping on the brake or accelerator."

Active safety technology must be developed based on elementary, time-consuming research such as analyzing basic factors causing accidents and driver behavior when accidents occur. Thus, conclusions cannot be reached in a short time. However, it is clear that **ABS** and **TCS** have the above-noted limitation, so technology that suppresses unstable vehicle behavior even when attempting to evade an accident using only steering wheel operations is necessary.

## **VSA DEVELOPMENT CONCEPTS**

Under these circumstances, **VSA** was developed from the following two points with the aim of significantly enhancing the active safety performance of conventional **ABS** and **TCS**.

(1) Ensuring that the driver can control the vehicle by stabilizing vehicle behavior through vehicle sliding, etc., even when neither braking nor accelerating is being performed.

(Adding new functions)

This point consists of working to stabilize vehicle behavior under various conditions by resolving the above-noted essential limitation with **ABS** and **TCS**.

(2) Further, working to enhance **ABS** and **TCS** performance by utilizing vehicle sliding and other measured information. (Enhancing the performance of existing functions)

In other words, controlling the tires so that they do not slip in the peripheral direction not only ensures sufficient lateral force but also actively stabilizes vehicle behavior, etc. This works to enhance the essential safety performance (stabilizing vehicle behavior) of **ABS** and **TCS**.

**VSA** development was based on the following three basic concepts.

### 1. The system should be simple and offer high reliability.

Reliability is a basic performance aspect of safety devices. Particularly for the **VSA** that aims to improve driver control, lack of reliability equals a critical loss of function. Therefore, the hardware configuration was made as simple

as possible from the viewpoint that simplification of the structure is one of the most basic methods of ensuring reliability.

### 2. The system should allow wide spread adoption.

It was thought that creating an easily affordable system would be a first in terms of proposing a new safety technology for a vehicle-based society. In addition, from the perspective of wide-spread adoption, the initial development assumed application in front-wheel-drive vehicles which have become the most common drive system in recent years.

### 3. The system should not interfere with the driver's operations or adversely affect the steering feeling.

In contrast to the basic stance of "how vehicles should be with respect to people," this system was based on the view that "the main force behind driving should be the driver." Therefore, this system places priority to the "person" without adversely affect the steering feeling by functioning only when the driver actually needs assistance.

## **SPIN & DRIFT OUT**

The longitudinal and lateral forces exerted by the tires determine vehicle motion, but these forces possess saturation characteristics. On the other hand, since the centripetal force required for turning is proportional to the square of the speed, the vehicle motion limits are dependent on the frictional limits of the tires.

All four wheels do not generally reach these frictional limits at the same time, and it is more common for either a front wheel or a rear wheel to reach their frictional limits first. Therefore, the phenomenon of unstable vehicle posture is broadly divided into instances where the front wheels reach their frictional limits first (the vehicle drifts toward the outside: drift out) and instances where the rear wheels reach their frictional limits first (the vehicle spins toward the inside: spin).

Which of the four wheels reaches its frictional limit first depends on various conditions such as the road condition and the vehicle speed. However, slipping of the tire essentially generates the tire force, so acceleration and deceleration produce vehicle spin and drift out. For example, if excessive driving torque is applied to a front-wheel-drive vehicle, causing the front wheels to spin, the front wheels reach their limits first when turning and the vehicle drifts out.

## **PRINCIPLE OF VSA**

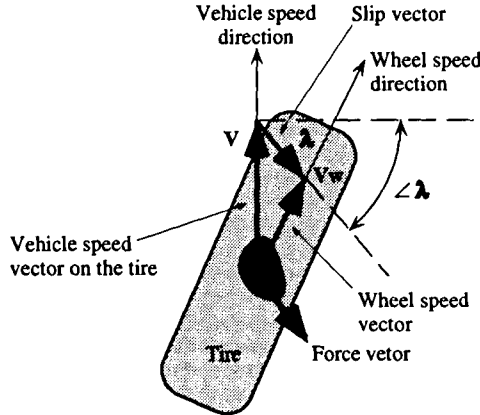
According to Reference (2) and other sources, controlling the traction of the each wheel can mitigate spin and drift out. Methods of controlling the traction of each

wheel include applying driving torque as mentioned in the above Reference, and applying braking torque to generate negative slip. However, if driving torque is automatically applied, the vehicle may accelerate against the driver's will, so the driving torque must be distributed. Therefore, this paper looks at stabilizing vehicle behavior by applying braking torque.

When theoretically analyzing vehicle behavior, it is first necessary to analytically consider the force exerted on the tires. This is often done using Fiala's theory, but this research introduced an original method to simplify the calculations in consideration of application to real-time simulations and other purposes. (This method is referred to here as the  $\lambda$ -METHOD.)

**Figure 3.** shows the results of calculating the manner in which peripheral slipping of the tires while turning affects the vehicle in the longitudinal and lateral directions using this method. This shows that the results calculated using the above-noted theoretical method match closely with the actual measured data.

This calculation method calculates the frictional force vectors acting on the wheel by transforming the relationship between the slip of the vehicle and the coefficient of friction (generally called the  $\mu - \lambda$  characteristic) into a planar slip vector. (**Figure 2.**)



**Figure 2. Vehicle speed, wheel speed, slip and force vectors.**

The planar slip vector ( $\lambda$ ) of the tire is:

$$\lambda = (\mathbf{Vw} - \mathbf{V}) / \max(|\mathbf{V}|, |\mathbf{Vw}|) \quad (1.)$$

and the force ( $\mathbf{f}$ ) acting on the tire is thought to generate the "size of the slip quantity function in the slip direction over the plane".

That is to say, the force ( $\mathbf{f}$ ) is expressed by the following equation:

$$\mathbf{f} = \mu(|\lambda|) \cdot \mathbf{Mg} \cdot \lambda / |\lambda| \quad (2.)$$

(Here,  $\mathbf{Vw}$  indicates the tire peripheral speed vector,  $\mathbf{V}$  the vehicle speed vector on the tire, and  $\mathbf{Mg}$  the vertical load. Also, in the equations used in this paper, vectors are indicated by thick characters, and scalar by thin characters.)

Here, the wheel peripheral speed is controlled by braking, so the wheel peripheral speed is  $K$  times ( $0 \leq K \leq 1$ ) the body speed.

$$|\mathbf{Vw}| = K \cdot |\mathbf{V}| \quad (0 \leq K \leq 1) \quad (3.)$$

Obtaining the frictional force when the wheel speed skids at the slip angle ( $\alpha$ ) with respect to the body speed results in the following equation.

$$\angle \mathbf{Vw} - \angle \mathbf{V} = \alpha \text{ (Wheel slip angle)} \quad (4.)$$

At this time,  $\lambda$  is:

$$|\lambda| = \sqrt{(K \cdot \sin \alpha)^2 + (1 - K \cdot \cos \alpha)^2} \quad (5.)$$

$$\angle \lambda = \arctan((1 - K \cdot \cos \alpha) / K \cdot \sin \alpha) \quad (6.)$$

Therefore, the coefficient of friction ( $\mu_x$ ) in the longitudinal direction with respect to the vehicle speed is:

$$\mu_x = \mu(|\lambda|) \cdot \sin(\angle \lambda) \quad (7.)$$

and the coefficient of friction ( $\mu_y$ ) in the lateral direction is:

$$\mu_y = \mu(|\lambda|) \cdot \cos(\angle \lambda) \quad (8.)$$

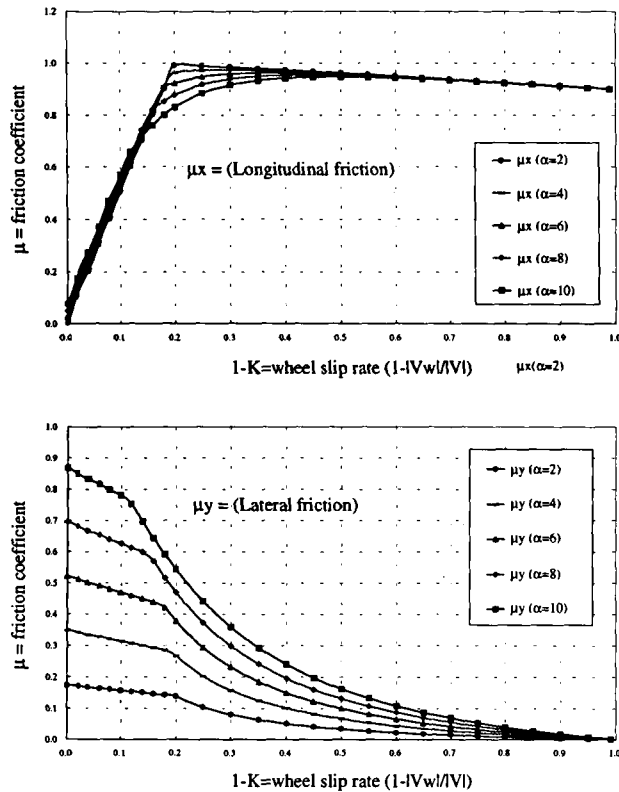
Here, the  $\lambda$  function of  $\mu$  was simplified and calculated using the following equation:

$$\begin{aligned} \mu &= (\mu_p / \lambda_p) \cdot \lambda & \{0 \leq \lambda \leq \lambda_p\} \\ &= (\mu_l - \mu_p) / (1 - \lambda_p) \cdot (\lambda - \lambda_p) + \mu_p & \{\lambda_p < \lambda \leq 1\} \end{aligned} \quad (9.)$$

(Here,  $\mu_p$  is the maximum coefficient of friction produced by the road surface, and  $\mu_l$  is generated using  $|\lambda| = \lambda_p$ . Also,  $\mu_l$  is the coefficient of friction when the wheel is locked.)

**Figure 3.** shows that the calculated and experimental results match closely, indicating that the force exerted by the tires can be easily obtained using the  $\lambda$ -METHOD even when turning with heavy braking that causes the wheels to lock.

**Figure 3.** indicates that the lateral coefficient of friction can be adjusted by controlling the above-noted K value, that is to say the wheel peripheral speed with respect to the body speed. Also, since this K value can be controlled in the range of 0 to 1 by applying the brake, this means that applying the brake to control the peripheral slipping of the wheel can control the lateral friction coefficient.



**Figure 3.**  $\mu - \lambda$  characteristic.

**Figure 4.** shows rough calculations of the effects on vehicle rotating motion when the brake is actually applied to one wheel.

This figure shows the calculated effects of braking force on vehicle rotation when **Figure 3.** is calculated for all four wheels and the K value of only one wheel is shifted in the range of 0 to 1 with the K value for the other wheels set to 0 (that is to say when braking is performed for only one wheel). The actual results differ somewhat due to the respective wheel load and the position from the center of gravity of the tire, but  $\tau_x$ ,  $\tau_y$  and  $\tau$  are calculated using the following equations for reason of simplicity.

$$\tau_x = \mu x_1 - \mu x_2 + \mu x_3 - \mu x_4 \quad (10.)$$

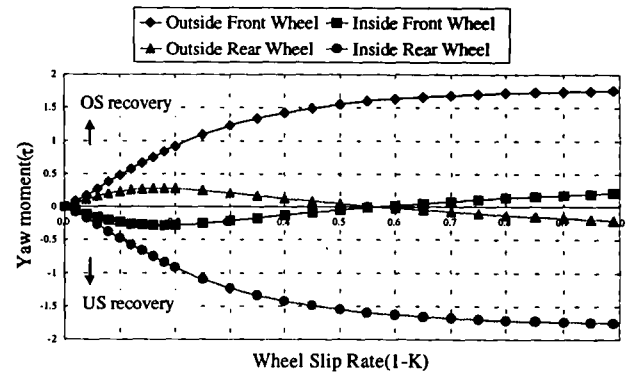
$$\tau_y = -\mu y_1 - \mu y_2 + \mu y_3 + \mu y_4 \quad (11.)$$

$$\tau = \tau_x + \tau_y \quad (12.)$$

{Subscripts:

1: Outside front wheel, 2: Inside front wheel,  
3: Outside rear wheel, 4: Inside rear wheel}

Here,  $\tau_x$  represents the braking force component that works as the yaw moment,  $\tau_y$  the lateral force component that works as the yaw moment, and  $\tau$  the sum of these components. When  $\tau$  is positive, braking generates a moment that rotates the vehicle to the outside; when  $\tau$  is negative, braking generates a moment that rotates the vehicle to the inside.



**Figure 4.** Effect of wheel braking on vehicle rotating

According to **Figure 4.**, outside front wheel braking suppresses the phenomenon where the vehicle attempts to rotate to the inside, and inside rear wheel braking suppresses the phenomenon where the vehicle attempts to rotate to the outside. This is the principle behind VSA that controls the vehicle posture by applying the brake to each wheel. **Figure 4.** also shows that the yaw moments of the inside front wheel and outside rear wheel braking forces change direction according to the wheel slipping. This is because the relationship between the direction of lateral force effect and the direction of braking force effect is reversed. For example, the braking force component of the outside rear wheel acts to point the vehicle toward the outside, but the drop in the lateral force component of the rear wheels acts in a direction that causes the vehicle to spin.

## Dynamic model simulation

To confirm the above results dynamically, dynamic vehicle reaction was simulated using the 4-wheel vehicle planar motion model shown below.

(Note that the force exerted on the tires was calculated using the previously mentioned  $\lambda$ -METHOD.)

$$\mathbf{V}_{wi} = R\omega_i \cdot \mathbf{A}(\theta + \delta_i) \cdot \mathbf{U}_x \quad (13.)$$

$$\mathbf{V}_i = \mathbf{V}_c + \mathbf{L}_i \cdot \gamma \cdot \mathbf{A}(\theta + \phi_i) \cdot \mathbf{U}_y \quad (14.)$$

$$d\mathbf{V}_c/dt = \Sigma \mathbf{A}(\theta) \cdot \mathbf{f}_i/M \quad (15.)$$

$$d\mathbf{X}_c/dt = \mathbf{V}_c \quad (16.)$$

$$d\gamma/dt = \Sigma \mathbf{L}_i \cdot \mathbf{U}_y^t \cdot \mathbf{A}(-\phi_i) \cdot \mathbf{f}_i/I_z \quad (17.)$$

$$d\theta/dt = \gamma \quad (18.)$$

Here,

$R\omega_i$  : Peripheral speed of each wheel

$\mathbf{L}_i$  : Distance between the tire position and CG.

$\phi_i$  : Angle of the tire position relative to CG.

$\delta_i$  : Actual steering angle of each tire

$\gamma$  : Yaw rate

$\theta$  : Yaw angle

$\mathbf{f}_i$  : Force exerted on the tires

$\mathbf{M}$  : Vehicle mass

$I_z$  : Moment of inertia around the Z axis

$\mathbf{V}_c$  : CG. speed vector

$\mathbf{X}_c$  : CG. position

$\mathbf{U}_x$  : x unit vector

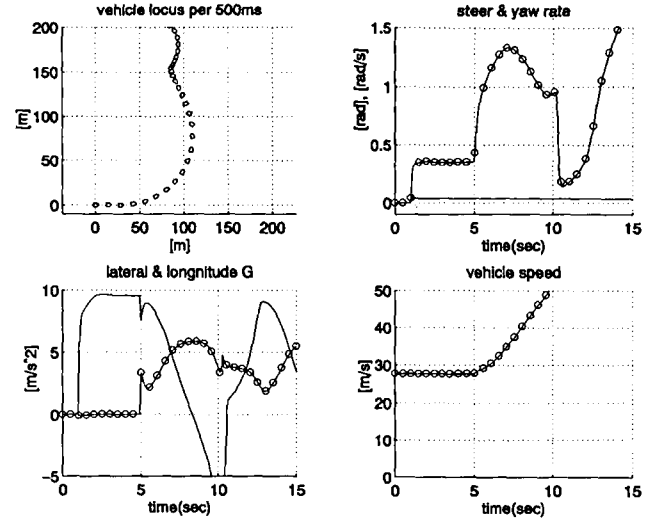
$\mathbf{U}_y$  : y unit vector

$\mathbf{U}_y^t$  :  $\mathbf{U}_y$  transposition vector

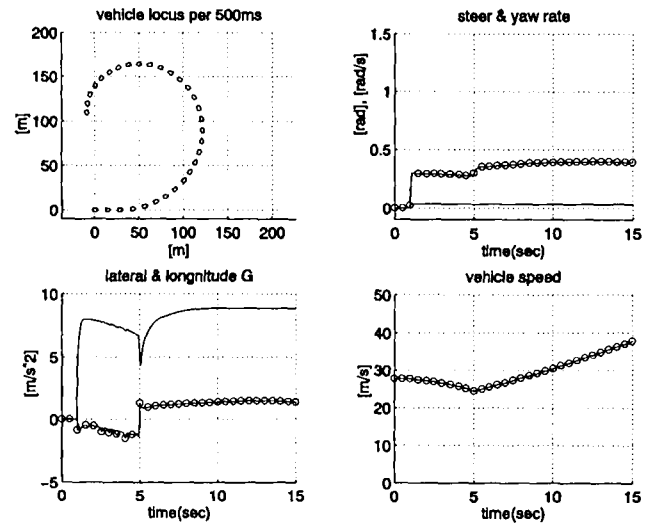
$\mathbf{A}(\theta)$  : Rotation matrix of angle  $\theta$

(CG.: The center of gravity)

**Figure 5.** shows the vehicle locus, acceleration, speed and yaw rate when acceleration slip is generated on the rear wheels while turning as obtained with this model. These results show that operating the accelerator inadvertently while turning causes a rear-wheel-drive vehicle to spin. **Figure 6.** shows the simulation results when braking slip is applied to the outside front wheel in accordance with the vehicle sliding angle ( $\beta$ ) under the same conditions as above. These results indicate that the vehicle can be turned without spinning even after applying sudden acceleration slip.



**Figure 5. Simulation results (without front-brake control)**



**Figure 6. Simulation results (with front-brake control)**

## METHODOLOGY OF VSA CONTROL (2CH CONTROL SYSTEM)

According to **Figure 4.**, outside front wheel braking is effective at suppressing an increase in the angle of rotation, and inside rear wheel braking increases the angle of rotation. Spin refers to the phenomenon where the angle of vehicle rotation exceeds the revolution angle, so it could be said here that outside front wheel braking suppresses spin. This has also been verified with the above-mentioned dynamic simulation.

However, it cannot be said that drift out is suppressed simply by inside rear wheel braking. That is to say, the driver senses understeer (a feeling of insufficient turning) not simply when the vehicle does not face toward the inside, but instead when the driver wishes to direct the turning locus more toward the inside. Thus, most cases of understeer are when the driver wishes to turn with a smaller turning radius. (Hereafter, this condition is called "over-speed understeer".)

**Figure 7.** shows the results of calculating how the turning posture and turning locus change during inside rear wheel braking. These results agree with those in **Figure 4.**, and show that while inside rear wheel braking effectively can increase vehicle rotation, it has little effect on the amount of lateral movement (equivalent to the turning radius).

In other words, even though braking suppresses changes in the vehicle posture, it is not very effective at reducing the turning radius.

Generally speaking, the resultant force exerted by the tires and the vehicle speed determined the locus of revolution. Thus, in order to reduce the turning radius, either increase the force exerted by the tires must be increased or the vehicle speed must be decreased. Realistically speaking, however, it is not possible to increase the frictional force exerted by the tires, so reducing the speed has a greater effect.

In contrast to this, it is also thought that "over-speed understeer" can be suppressed by reducing the vehicle speed by applying the brake to four or some wheels ("deceleration control").

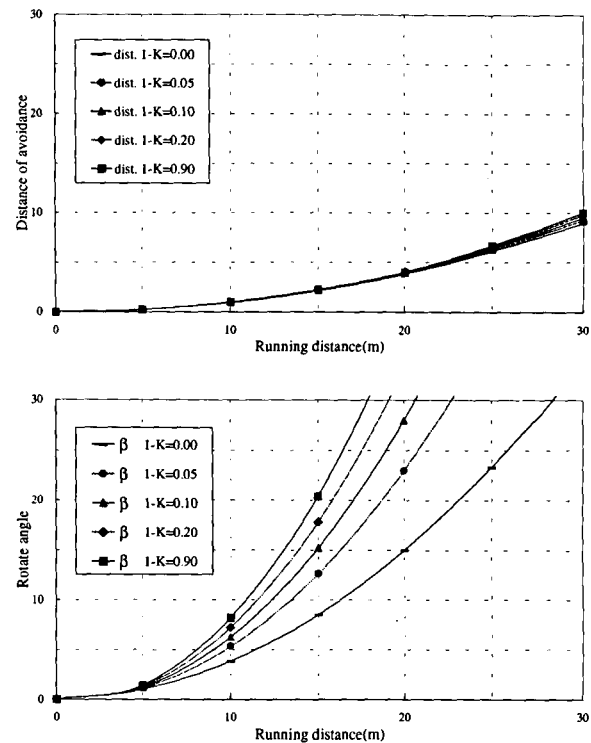
However, even if the speed is reduced, the deceleration has limit by the road friction, so it is not always possible to obtain the desired revolution locus. Further, the inability to negotiate a curve occurs easily on wet, snow-packed or other slippery road surfaces, so there is little reduction in speed in these cases.

In other words, unless the speed at which the next curve can be negotiated or where the driver is attempting to go can be predicted in advance, "deceleration control" cannot completely suppress "over-speed understeer".

In addition, the fact that this system may give the driver the false impression of being able to negotiate an impossible curve must also be taken into account. Drivers are generally thought to apply the brakes when they determine that a curve cannot be negotiated. Therefore, it was felt that efforts should

be made to enhance safety by improving ABS performance rather than by "deceleration control".

On the other hand, accelerator operations easily cause front-wheel-drive vehicles to drift out ("acceleration-understeer"), making TCS performance, or suppressing peripheral slipping of the tires, important for increasing behavior stability. This "acceleration- understeer" can be effectively suppressed by controlling front wheel slip independently for the right and left wheels by braking ("Braking TCS").



**Figure 7. Effects of inside rear wheel braking on wheel reaction.**

Summarizing the above points:

- 1) Vehicle spin can be suppressed by outside front wheel braking.
- 2) Inside rear wheel braking alone has little effect on suppressing drift out.
- 3) Assuming a front-wheel-drive vehicle, the desired effect can be achieved by applying pressure to only the front wheels with "Braking TCS".

Therefore, controlling the braking pressure to the two front wheels and controlling the engine torque realizes a simple yet highly effective system for front-wheel-drive vehicle is one of the development concepts.

## CONSTRUCTION OF THE VSA SYSTEM

Based on the above results, we constructed VSA by expanding the ABS and TCS with a yaw rate sensor and lateral accelerometer that directly measure the vehicle posture, a steering angle sensor and other sensors that estimate the driver's turning intention, and a hydraulic unit for independently pressurizing the front wheels. The ECU (Electrical Control Unit) was also expanded. (Figure 8.)

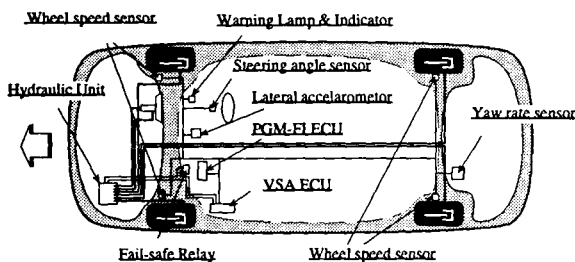


Figure 8. Construction of the VSA system.

The yaw rate sensor is a vibrating type whose reliability and accuracy have been enhanced for vehicle control. This yaw rate sensor is important because it sensor directly measures the vehicle's rotation, so a self-diagnosis circuit has been provided inside the sensor to improve system reliability. (Figure 9.)

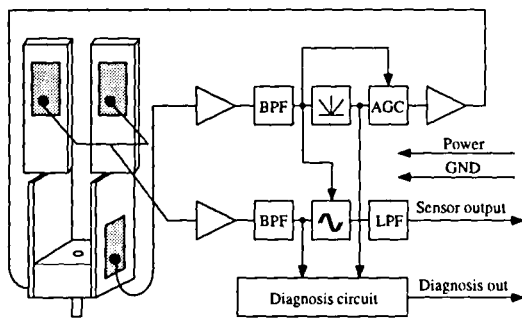


Figure 9. Yaw rate sensor

The lateral accelerometer and steering angle sensor are those used in the conventional TCS, but thorough FMEA (Failure Mode, Effect Analysis) there have been implemented inside the sensors to further improve reliability.

The VSA hydraulic units add a pressurizing unit onto the conventional ABS unit for a simple and compact structure. These two units have independent oil routes and are coupled via a pressurizing piston. The pressurizing units pressurize calipers that are linked to the ABS units by using pressurizing pistons and both the ABS pump and the VSA pump are driven one motor and one axle.

The pressurizing pistons transmit the higher of the pressures generated by the master cylinder or the pressurizing unit to the calipers. This allows braking to be performed according to the driver's intention even when the driver brakes suddenly during pressurization. Further, the pressure from the pressurizing unit is transmitted when vehicle behavior becomes unstable even during ABS operation or other braking, thus ensuring VSA operation. (Figure 10.)

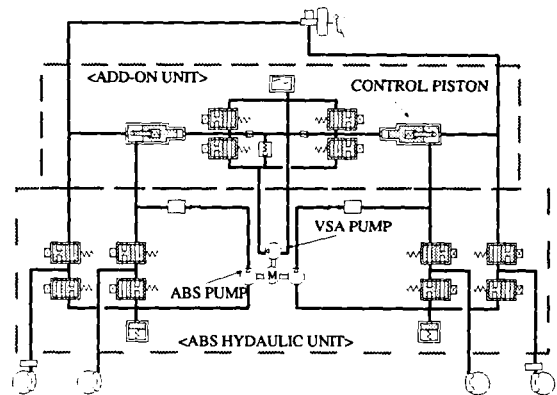


Figure 10. Hydraulic unit.

The ECU is comprised of a 16-bit main CPU (Central Processing Unit) and an 8-bit sub-CPU. Each CPU performs operations independently to ensure safety when making particularly important decisions. (Figure 11.)

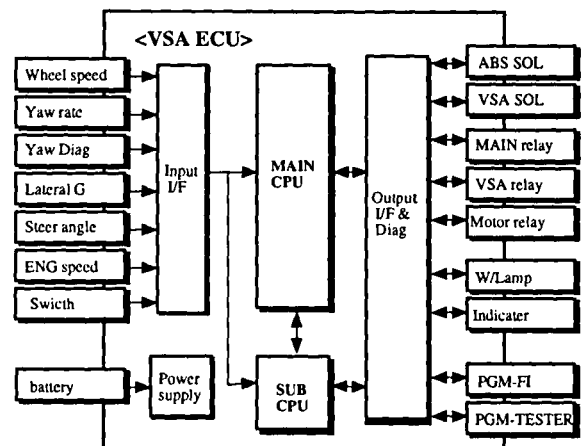


Figure 11. ECU block diagram

## VSA CONTROL SOFTWARE

VSA control software is comprised of three blocks. The first of them is a control block that determines the vehicle posture from the yaw rate, lateral acceleration, steering angle, vehicle speed, etc. The second is the ABS/TCS control block that determines how to adjust the braking force based on the peripheral slippage of the wheels. And the third is an output control block that drives the pressurizing and ABS units based on the posture and braking pressure adjustment judgments, and at the same time communicates with the engine control unit to adjust the engine torque. (Figure 12.)

The vehicle posture is basically determined from the sliding angular rate of the vehicle. The centripetal acceleration while the vehicle is turning is proportional to the square of the speed and inversely proportional to the turning radius. In addition, the turning angle rate (revolution angular rate) as viewed from the inertia coordinate is proportional to the speed and inversely proportional to the turning radius.

Here, if the advancing speed and direction of the vehicle do not differ greatly from the vehicle direction, the revolution angular rate is obtained by dividing the centripetal acceleration, which is detected as a reaction force by the lateral accelerometer, by the speed.

On the other hand, the rotational motion of the vehicle is not restrained by the revolving motion, and is determined by the balance of the forces exerted on each wheel. The yaw rate at this time can be directly detected by sensing the Coriolis force generated with respect to the vibrating speed of the sensor trembler.

The turning angle rate does not greatly differ from revolution angular rate during normal turning. However, these rates differ greatly when the vehicle slides for whatever reason, making it possible to determine the vehicle posture by comparing the two.

In other words, the turning angle rate is greater than the revolution angular rate during spin, and this relationship is reversed during drift out. (Figure 13.)

On the other hand, when the speed is gradually increased from the condition of cornering at a constant speed, the condition where the steering angle must be increased is sometimes referred to as understeer, and the opposite as oversteer. Assuming cornering, the turning radius does not change so the revolution angular rate is proportional to the advancing speed. Therefore, this mode understeer (drift out) or oversteer (spin) can be judged by comparing the product of the steering angle and the speed with the actual yaw rate. The vehicle posture judgment block combines the above two judgment methods to comprehensively judge the sliding angular rate of sprung mass and the estimated driver's intent. At the same time this block also calculates the amount of sliding to be applied to the tires and the amount of engine torque adjustment based on this judgment.

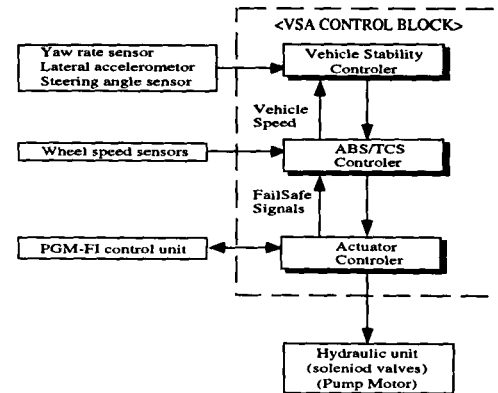


Figure 12. Control block diagram

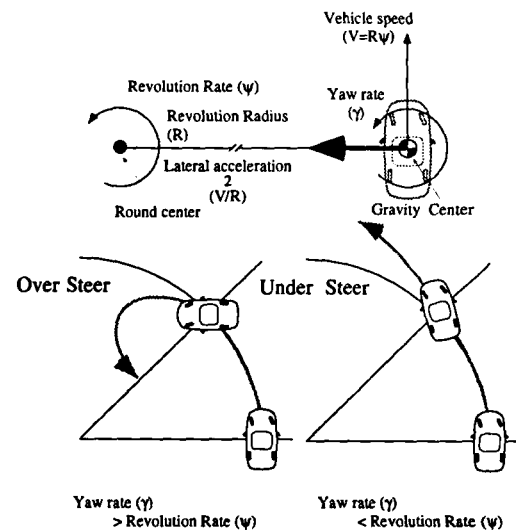
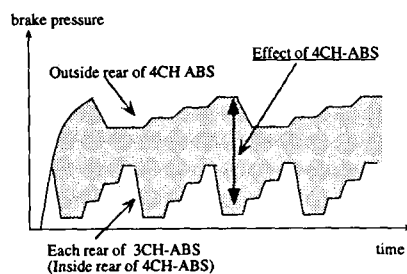


Figure 13. Yaw rate and revolution angular rate

The **ABS/TCS** control block compares the wheel speed with the body speed which is estimated from the wheel speed, and weakens the braking force if it determines that the wheels are likely to lock when the wheel speed is much slower than the body speed. This block also determines that the wheels are spinning and either lowers the engine torque or applies the brakes when the wheel speed is much faster than the body speed. Further, performance is enhanced compared to individual **ABS/TCS** operation by varying the **ABS/TCS** target slip according to the information from the posture judgment block. For example, normal **ABS** controls both rear wheels according to the wheel that slips the easiest. In contrast to this, **VSA** increases the deceleration rate and ensures stable braking by switching to 4CH independent **ABS** when there is judged to be sufficient rear lateral force margin when making a high-G turn. (Figure 14.)



**Figure 14. Effect of 4CH-ABS**

In addition, if vehicle spin is detected during **ABS** operation, stable braking during a turn is ensured by increasing the target slip of the outside front wheel according to the degree of spin. This is an application of the principle shown in **Figure 4**.

This is because whereas **ABS** assumed that wheel slip less generally experience greater lateral force, it is sometimes easier to stabilize the vehicle by increasing the slipping depending on the vehicle balance. As for **TCS** control, when the generated yaw rate is small compared to the steering angle, the target slip is reduced, making it easier to generate lateral force. In addition, when vehicle spin is detected, **VSA** increase target slip of **TCS** so as not to interfere with acceleration based spin avoidance actions by the driver.

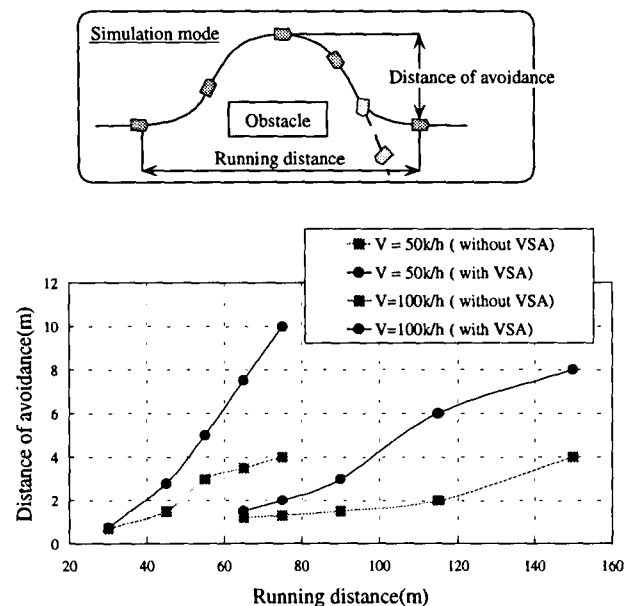
Further, even when the wheels are not slipping in the peripheral direction, if the vehicle posture judgment block determines that automatic braking is necessary, it signals the **ABS/TCS** control block which generates slipping on the brake side for one of the front tires.

The output control block finely controls the solenoid valves of the **ABS** and the pressurizing units and at the same time controls the hydraulic pumps and the hydraulic units to produce the slip requested by the **ABS/TCS** control block.

It is based on the results calculated by the **ABS/TCS** control block. In addition, the output control block also communicates with the engine control unit to perform the engine torque adjustment calculated by the **ABS/TCS** control block.

## EFFECTS OF VSA

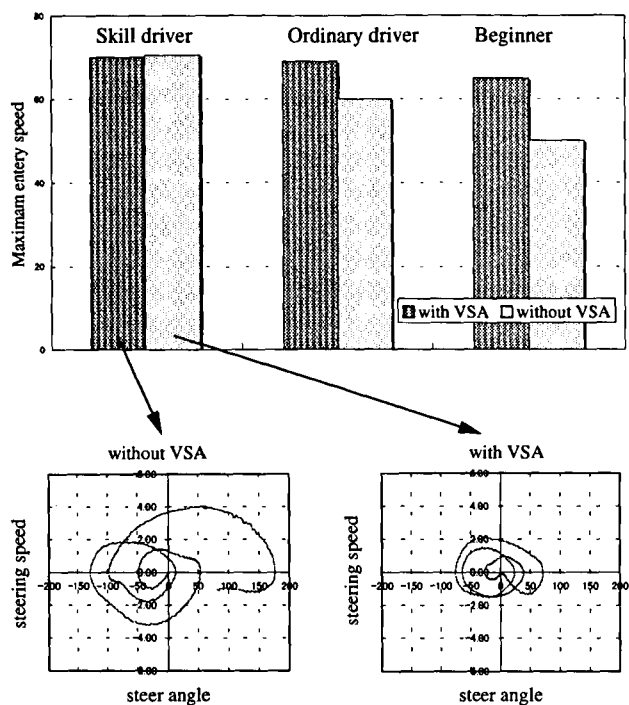
**Figure 15**. shows the results of simulating the amount of avoidance that can be performed without causing spin during open loop steering when there is no corrective steering by the driver. Actually, it is impossible to have absolutely no corrective steering when spin occurs as assumed by this simulation. However, this simulation shows that the **VSA** system roughly doubles the allowable avoidance amount under conditions of this type of limited simple steering.



**Figure 15. Capacity of crash avoidance. (simulation result)**

**Figure 16**. shows the results of actual vehicle tests when the driver performed corrective steering. This figure shows the speed at which a double lane change can be performed on a low- $\mu$  road surface equivalent to a snow-packed road. These results differ from **Figure 15**. in that there is almost no difference either with or without **VSA** when corrective steering was performed by a skilled driver. However, it was found that the amount of steering operations through the double lane change decreased markedly with **VSA**. In addition, these test results also revealed that **VSA** made it possible for an ordinary driver to drive at roughly the same





**Figure 16. Lane-change performance: maximum entry speed and steering operation quantity (Vehicle test under ISO double lane change)**

speed as a skilled driver.

Figure 15. and Figure 16. indicate that VSA assists driver operations to make driving operations possible during critical behavior as typified by emergency evasion. On the other hand, however, these results also proved that VSA does not raise the physical limits.

## CONCLUSIONS

- (1) This paper introduced an original tire model, and confirmed that the VSA principle can be verified using the principle of this model ( $\lambda$ -METHOD).
- (2) A simple but highly efficient system was constructed by controlling the braking pressure to the front two tires and controlling the engine torque.
- (3) VSA was confirmed to assist driver operations during critical behavior through simulations and actual vehicle tests.

## ACKNOWLEDGMENTS

We feel that VSA can help to improve vehicle safety by stabilizing the vehicle posture and assisting driver operations under conditions involving vehicle sliding where steering is ordinarily considered difficult.

However, the VSA system cannot raise the physical limits determine the produced frictional force and the inertia

of the vehicle, and the final route determination must be made by the driver. Further, current systems are unable judge whether it is physically possible to realize the driver's intentions.

We feel that it is important to enhance collision safety performance and at the same time perform further research and development concerning active safety to determine how far people can be supported from the vehicle side. On the other hand, we feel it is also important to carry out comprehensive activities to improve automobile safety including activities to educate drivers and encourage safe driving.

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# **ADAPTABILITY TO AMBIENT LIGHT CHANGES FOR DROWSY DRIVING DETECTION USING IMAGE PROCESSING**

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Paper Number 98-S2-P-15

## **ABSTRACT**

A drowsy driving warning system has been developed that uses image processing technology to calculate the blink rate of the driver's eyes. One issue that had to be addressed in developing this system was to ensure sufficient adaptability to ambient light changes in the passenger compartment during driving. The aim of the present work was to develop an image processing algorithm capable of coping with such ambient light changes. The results of drowsy driving detection tests conducted with an actual vehicle have confirmed the effectiveness of the detection algorithm.

## **INTRODUCTION**

There are various methods that can be used to detect drowsy driving. These detection methods can be broadly divided into two categories. One category makes use of information about the driver such as psychological signals; the other category uses information about the vehicle such as the operation of vehicle control systems or vehicle motions. Typical examples of physiological signals include brain waves, eye electric potential, heart rate and skin electric potential. Driving operations such as the movement of the steering wheel or the operation of the accelerator or brake pedal can be sensed, and characteristics for identifying drowsy driving can be detected. Detectable vehicle motions stemming from drowsy driving include the vehicle speed, lateral acceleration, yaw rate and lateral displacement, among others.

Measurement of physiological signals provides a rather accurate means of detecting drowsy driving, but it is necessary to attach sensors directly to the driver's body. Methods based on the use of vehicle information offer the advantage of noncontact detection, but they are subject to severe limitations depending on the characteristics of the vehicle or the driving environment.

Taking these issues into account, it was decided to use image processing technology to detect drowsy driving.

The reason for this choice is that it offers the advantages of not causing the driver any discomfort or annoyance and of providing high detection accuracy.

## **OVERVIEW OF DROWSY DRIVING DETECTION AND TECHNICAL ISSUES**

The drowsy driving detection system consists of a CCD camera that takes images of the driver's face and a controller that detects drowsy driving by determining the eye positions from the driver's facial image and judging the open or closed state of the eyes.

This type of drowsiness detection system based on the use of image processing technology must be able to accommodate individual driver differences as well as the use of glasses. Likewise, it must also be able to adapt reliably to changes in the ambient light in the passenger compartment between day and night and depending on the weather, the height of the sun and other factors. When light is uniformly distributed over the driver's face, facial images have distinct gray scale values, making it relatively easy to detect the eye positions and to judge whether the driver's eyes are open or closed. However, when a portion of the driver's face is exposed to direct sunlight, the contrast between the eyeballs and the surrounding skin is weaker both on the side bathed in sunlight and on the side in the shadow. This reduced contrast makes it difficult to detect the eyes simply on the basis of gray scale information extracted from the facial image. In this case, because sunlight is not reflected evenly, it is not possible to process the entire facial image uniformly either with absolute gray scale values or with relative values such as the average gray scale value of the entire image.

The aim of this research was to devise an algorithm for resolving this issue and to confirm that a system incorporating the algorithm would be able to detect drowsiness reliably under varying ambient light conditions.

## **DETECTION ALGORITHM**

The flowchart in Figure 1 shows the main sequence of operations performed by the drowsy driving detection system. This system consists of two main functions. One is a function for detecting the eyeball positions from the overall facial image data. The other is a function for detecting drowsy driving by monitoring and confirming changes in the open or closed state of the eyes.

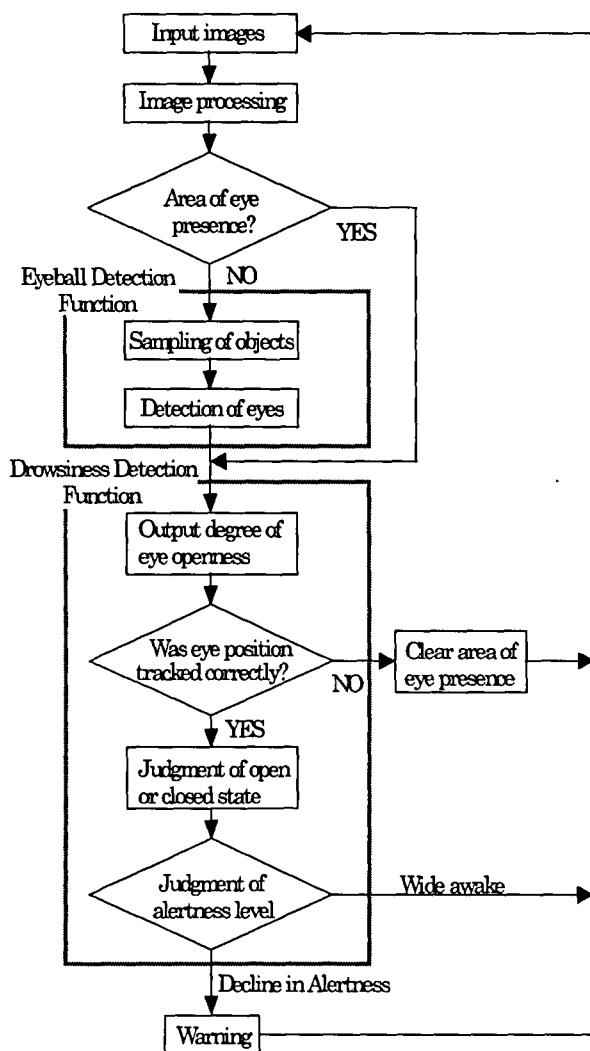


Figure 1. Flowchart.

### Eye Position Detection

The details of the process for detecting the positions of the driver's eyes are explained here in reference to Figure 2. The image of the driver's face photographed with the CCD camera is initially stored in an image memory. Gray scale values in the vertical direction are then read out from the image data, as indicated in Figure 2-(a). The changes in the gray scale values along line Xa in Figure 2-

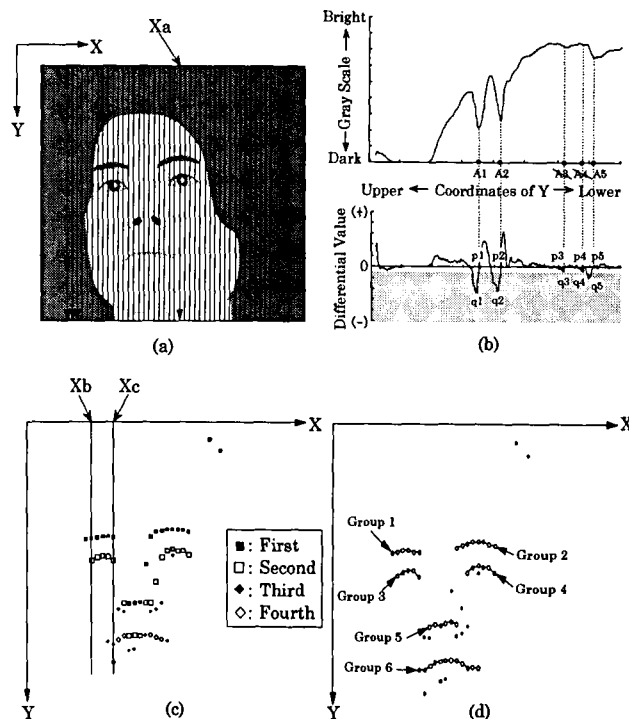


Figure 2. Method of Detecting Eye Positions.

(a) are shown in Figure 2-(b). Feature points are then extracted along each line from these changes in the gray scale values. The feature extraction method is explained in reference to Figure 2-(b). Changes in gray scale values to darker features representing the eyebrows, eyes and other parts of the face are indicated by the downward projections in the graph. Accordingly, these features can be detected as the points denoted as p1 to p5 in the differential value graph where the values change from negative to positive.

However, the dark portions along any arbitrarily chosen vertical line also include shaded areas due to uneven facial contours, in addition to an eye or an eyebrow. Consequently, the degree of change in the gray scale values toward the darker feature points of interest is judged on the basis of the level of the negative differential values, in order to remove shadows and other unwanted noise. A specific example is explained here in reference to Figure 2-(b). It is seen that there are five points, denoted as p1 to p5, where the differential values change from positive to negative. On the other hand, the minimum differential values (q1 to q5), indicating the degree of change in the gray scale values toward those points, do not reach the specified level (i.e., do not enter the gray shaded area) at q3 and q4, so p3 and p4 are removed. As a result, the three points A1, A2 and A5 are obtained as the feature points of line Xa. The feature points extracted in this manner along each vertical line are

shown in Figure 2-(c). Two points have been extracted along line Xb and four points have been extracted along line Xc. The feature points are then grouped as shown in Figure 2-(d) according to the degree of vertical contiguity with the feature points of each adjacent line. When this grouping operation is performed, attention is focused only on those groups having a length longer than a certain specified value. This is because it is known that the eyes can be recognized as features having a long horizontal length. Simultaneously, the central coordinate values, length and other characteristics of each group are stored in memory as reference values of each group's data. The positions of the eyes are detected by using these reference values to select data corresponding to the eyes. An example of the feature points extracted in this manner is shown in Figure 3.



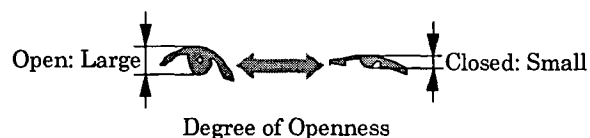
**Figure 3. Example of Processed Image.**

#### **Detection of Open/Closed State of the Eyes**

An outline is given here of the process for judging the degree to which the driver's eyes are open or closed. This process consists of the following four steps.

- (1) Based on the eye positions detected in reference to each group's data, small rectangles are defined as the areas where the eyes are present. The feature points in each rectangle are extracted by the same process as that explained in section 3.1.
- (2) A gray scale range is set by using the minimum differential values that represent the level of change in gray levels toward the feature points.
- (3) The number of continuous pixels in the vertical direction judged to be the dark portion of the eyes is used to calculate the degree of eye openness (Figure 4).
- (4) Judgement of whether the eyes are open or closed is based on the calculated degree of eye openness.

Following this judgment, the areas in which the eyes are present are set based on the central coordinates of the eye group data, and the process then proceeds to input the next facial image. This procedure makes it unnecessary to detect the eye positions each time once they have been identified, because eye data will also be included in the areas of eye presence in the next facial image, so long as there is no large movement of the driver's face. The degree of eye openness used to detect the open/closed state of the eyes changes only in a limited range for a specific driver. Consequently, if a value exceeding that range is calculated, it can be judged that the eye positions have not been detected correctly. When such a judgment is made, the areas set for eye presence are cleared, and the process returns again to the step of detecting the positions of the eyes from the entire facial image.



**Figure 4. Method of Judging Open or Closed State.**

#### **Method of Adapting to Ambient Light Changes**

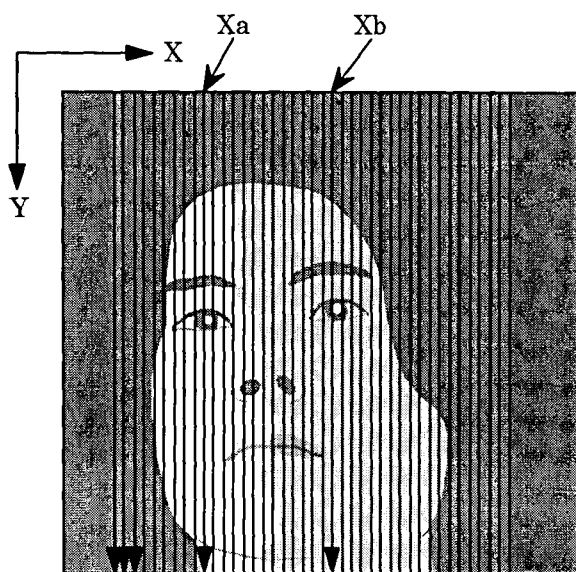
The method explained above for detecting the eye positions and open/closed state of the eyes uses relative gray scale values as the condition for extracting the feature points along each line. Therefore, it can extract the feature points according to each place in the facial image even if the ambient light balance over the entire face is poor. A specific example of the method of adapting to ambient light changes is shown in Figure 5.

The vertical lines Xa and Xb indicate the portion of the face exposed to direct sunlight and the portion in the resulting shadow, respectively. Even in this case, the points where the gray scale values become partially darker can be reliably extracted by processing each line, as shown in Figure 6. An example of the extracted feature points is given in Figure 7.

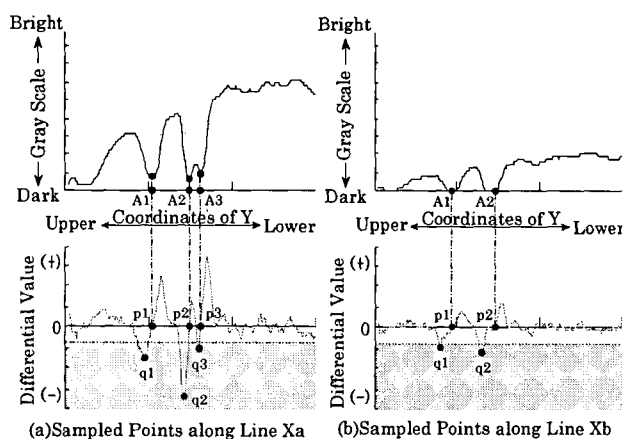
An infrared lamp is used as an auxiliary light source to compensate for the insufficient amount of ambient light at night or when driving through a tunnel. This makes it possible to detect the eye positions and the open/closed state of the eyes just as is done during the daytime. An example of the feature points extracted at night with the use of the infrared lamp is shown in Figure 8.

#### **Accommodation of Glasses**

A separate issue that had to be considered for



**Figure 5. Variation in Ambient Light on a Facial Image.**



**Figure 6. Method of Adapting to Changes in Ambient Light.**

drivers who wear transparent lens glasses was the fact that the frames would become noise that would add another possible feature candidate in the process of detecting the eye positions. The decline in contrast between the eyes and the surrounding skin due to the reflection from the lenses of the glasses, on the other hand, can be treated in the same way as changes in the ambient light in the passenger compartment. Accordingly, the procedure explained in section 3.3 is fully sufficient in this regard. An example of the feature points extracted for a driver who was wearing glasses is given in Figure 9. One method of resolving this separate issue of how to select the eyes from among feature points that include many noise candidates is to recognize the shape of the lower



**Figure 7. Example of Processed Image Daytime: Lighted & Shaded.**



**Figure 8. Example of Processed Image Nighttime: with an Infrared Lamp.**



**Figure 9. Example of Processed Image Wearing Glasses.**

portion of the frames as a feature candidate with a downward projection. Accordingly, the proposed system can detect the eye positions and the open/closed state of the eyes even in the case of drivers who are wearing glasses with transparent lenses coated with an antireflection treatment.

## EVALUATION TESTS

### Test Method

The drowsiness detection performance of the system was evaluated in laboratory tests and driving tests. In the former tests, drowsiness was induced in the subjects by having them perform a simple tracking task and in the latter tests by having them drive under monotonous conditions.

The configuration of the experimental drowsiness detection system is shown in Figure 10. It consisted of a camera for photographing images of the driver's face, a controller for detecting a drowsy driving condition by determining the eye positions from the facial images and judging the open/closed state of the eyes, and a warning buzzer for alerting the driver when the controller detected drowsy driving. An infrared lamp was installed as a nighttime light which did not interfere with driving operations.

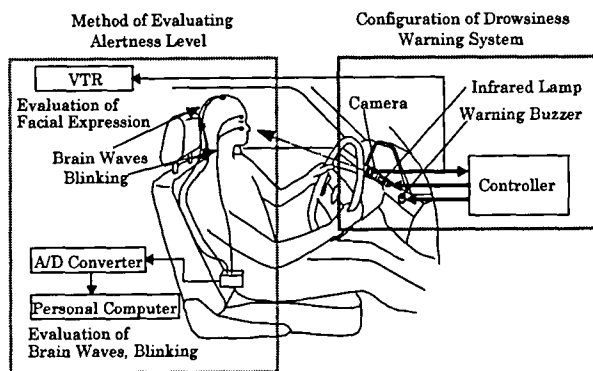


Figure 10. Configuration of Experimental System.

**Laboratory Tests** - Tests were conducted using a trimmed body with the windows covered to darken the interior. The subjects operated the steering wheel and the accelerator pedal to perform a simple tracking task on a CRT screen which was installed in front of the driver's seat. This experiment was conducted with the infrared lamp in a completely dark room so as to create conditions simulating nighttime driving.

**Driving Tests** - The subjects were asked to drive at

a constant speed on a course around the periphery of the proving ground. This monotonous driving condition induced a natural state of drowsiness.

### Quantification of Alertness Index

The performance of the system in detecting drowsy driving was evaluated on the basis of an alertness index, shown as the left-hand scale in Figure 11. This index was used to judge a subject's alertness level quantitatively, based on the total of the evaluation scores assigned to brain waves ( $\alpha 2$ ), eye electric potential and facial expression, which are known to vary according to a person's level of alertness. A state of reduced alertness was defined as an alertness index value of 6.0 or lower. (1)

### Test Results

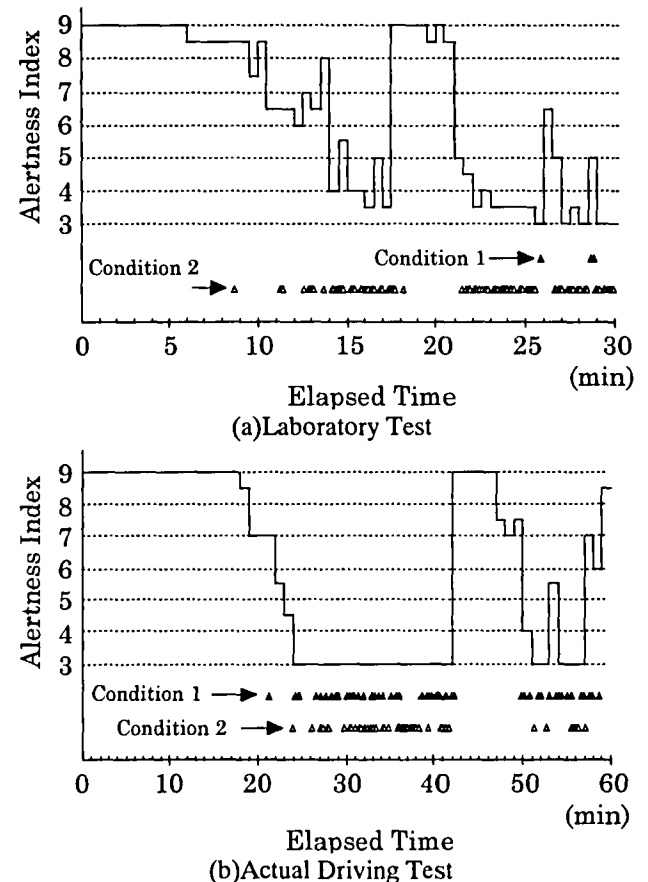


Figure 11. Evaluation of Drowsiness Detection Performance.

The rate at which the eyes blink changes as a driver becomes drowsy at the wheel. Blinking declines from a rapid rate characteristic of a wide-awake condition to a

slow rate as the level of alertness drops. In these tests, drowsiness detection performance was evaluated on the basis of two conditions that focused on the duration of eye closure. Condition 1 was defined as a case where the cumulative eye closure time at a somewhat slow blink rate (0.2 sec. or greater) exceeded a specified value within a given interval of 30 sec. Condition 2 was defined as a case where the eyes closed for a rather long interval of 1.5 sec. or more. The detection performance of the system was evaluated using the above-mentioned alertness index as the criterion. Examples of the detection results obtained in each type of test are shown in Figure 11.

Although drowsiness warnings were not issued to the subjects when conditions 1 and 2 were detected in the tests, the results suggest that reduced states of alertness corresponding to these two defined conditions were accurately detected in both types of tests. While condition 2 frequently appeared in both the laboratory and driving tests, it should be noted that condition 1 did not occur very frequently in the laboratory tests. It is thought that the reason for this can be attributed to the difference in the tasks required of the subjects in the two types of tests. In the laboratory tests, since the subjects were only given a simple task involving the operation of the steering wheel and the accelerator pedal, they may have felt secure in closing their eyes for longer intervals. Compared with that situation, in the driving tests they could not safely allow themselves to become sleepy while operating an actual vehicle. Accordingly, it can be concluded that a long eye closure interval is not likely to occur at the onset of drowsiness during real-world driving.

## CONCLUSION

An algorithm for detecting drowsy driving was developed and its adaptability to ambient light changes was confirmed.

Test results verified the effectiveness of this algorithm for detecting drowsy driving on the basis of long eye closure and a slow blink rate as the detection conditions.

It was confirmed that the detection algorithm is also effective for drivers who wear glasses, although the problem of having to select the eyes from among many feature candidates remains an issue to be addressed for this type of driver.

One issue that must still be resolved is to devise a more accurate procedure for detecting the eye positions by taking into account individual driver differences. Nonetheless, the results of the present work indicate that the practicality of this drowsy driving detection system has been improved.

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# DEVELOPMENT OF TIRE PRESSURE MONITORING SYSTEM USING WHEEL-SPEED SENSOR SIGNAL

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Paper Number 98-S2-P-16

## Abstract

It is difficult for today's motorists to detect a loss of tire pressure since a gradual tire pressure loss occurring on four wheels at the same time (natural leak) accounts for a large proportion of the tire pressure loss incident.

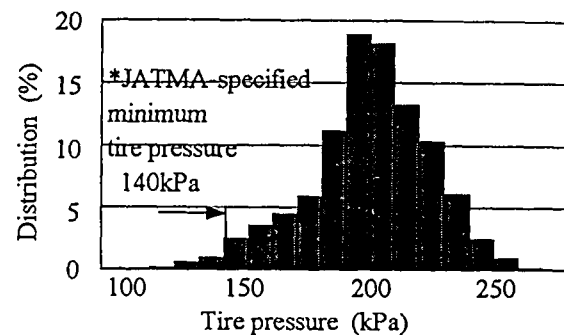
To help overcome this difficulty, we have developed a tire pressure monitoring system using the wheel-speed sensor signal of the ABS system. The monitoring system is low in cost and is capable of detecting the simultaneous air pressure loss on four wheels.

## Background to R&D Effort

It seems that today's motorists are paying less and less attention to tires since the improved performance of tires has reduced the natural tire pressure loss and consequently reduced the incidence of puncture.

Nonetheless, there is a natural loss of tire pressure at around 5-10 kPa/month. With an additional tire pressure change caused by the change in ambient temperature (approx. 10 kPa/10°C), the driver may experience low tire pressure without knowing it.

Fig. 1 shows the results of the survey on the tire pressure of the cars parked at the employee's parking lot of our affiliated company. 4.4% of these cars had the tire pressure of 140 kPa or less, and about 64% of which (or 2.8% of the cars surveyed) had nearly the same tire pressure for four wheels (natural leak). On the other hand, 0.2% of total cars surveyed had the tire pressure difference of 50kPa or more among four wheels.



\*JATMA : The Japan Automobile Tire Manufacturers' Association, INC.

Fig. 1 Results of Survey on Distribution of Tire Pressure

Table 1 shows the number of on-site services by Japan Automobile Federation (JAF) for tire trouble.

JAF made about 3,800 on-site services per week or about 200,000 services when simply translated into yearly terms on general roads and expressways.

Table 1 Causes for Calling the JAF Rescue Service (Weekly Basis)

Cause of trouble	General roads		Expressways	
	Number of cases	% total	Number of cases	% total
Tire	2783	3.64	1069	11.75
Fuel shortage	970	1.27	732	8.05
Locked-in key	25316	33.09	415	4.56
Traffic accident	4532	5.92	533	5.86
Battery	18012	23.55	703	7.73

August 1996



Since long-range driving of a car with under-inflated tires will lead to deterioration in stability, controllability and fuel economy, acceleration of tire wear and tire burst, a number of tire pressure loss detection systems have been commercialized in the recent years.

One such system consists of a pressure sensor mounted inside the tire to directly measure the tire pressure.

It is highly accurate but has yet to be popularized due to its high cost. The recently-commercialized monitoring system that uses the tire revolution difference data transmitted by the wheel-speed sensor of ABS (which is similar to our system) has succeeded in reducing the cost, but it can not detect the simultaneous loss of tire pressure on four wheels (natural leak) since the system is based on relative determination of the conditions of four tires.

### Principle of Detection

Fig. 2 shows the power spectrum density (PSD) of the wheel-speed sensor signal at the standard air pressure (200 kPa) and the low air pressure (100 kPa).

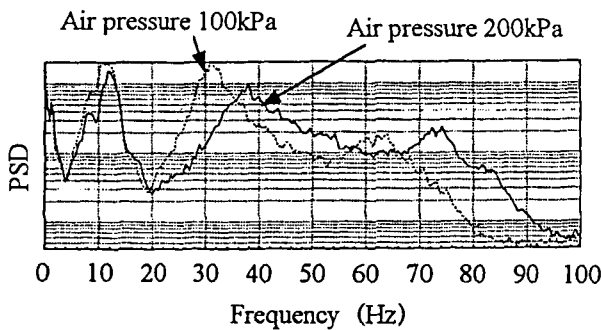


Fig. 2 PSD of Wheel-Speed Sensor Signal

As the air pressure changes, the peak frequency in the frequency band of 30 to 40 Hz varies. This variation is probably due to the coupled vibration of tire and suspension since this frequency band nearly overlaps with the longitudinal acceleration.

If the variation in resonance frequency is detected, a change in the tire pressure can be detected. However, a significant volume of data will be required to obtain stable results, and this means greater workload on the on-board electronic control unit (ECU) which will limit the cost reduction effort.

Fig. 3 shows the relationship between the spring constant in the direction of the rotation of the tire and the tire pressure as determined in the hammering test of an individual tire. The chart shows that the spring constant almost changes in proportion to the tire pressure.

A tire model can be constructed on the basis of these results, and by using this model, the amount of variation of the torsional spring.

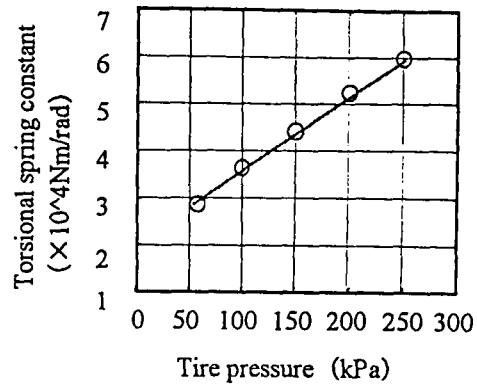


Fig. 3 Relationship between Torsional Spring Constant and Air Pressure of Tire

### Tire Model

Fig. 4 indicates the tire model used for our system.

In this model,  $J_1$  is the moment of inertia on the rim side,  $J_2$  is the moment of inertia on the belt side,  $K$  is the torsional spring constant of the tire,  $D$  is the equivalent viscous damping coefficient of the tire,  $\omega_1$  is the rotational speed on the rim side (detectable),  $\omega_2$  is the rotational speed on the belt side,  $\theta_s$  is the torsional angle and  $T_d$  is the road surface disturbance.

The equation of state for this diagram is shown below:

$$\begin{cases} J_1 \dot{\omega}_1 = -K(\theta_1 - \theta_2) - D(\omega_1 - \omega_2) \\ J_2 \dot{\omega}_2 = K(\theta_1 - \theta_2) + D(\omega_1 - \omega_2) - T_d \\ \theta_s = \theta_1 - \theta_2 \end{cases} \quad (1)$$

The variation of the spring constant  $K$  in this equation from the standard value is estimated by the external disturbance observer and the least-squares method.

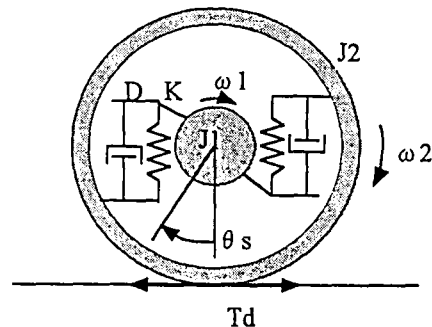


Fig. 4 Tire Model

The block diagram of the estimation procedure is shown in Fig. 5. In this diagram, the pre-filter is a band path filter that separates the resonance component from the wheel-speed sensor signal.

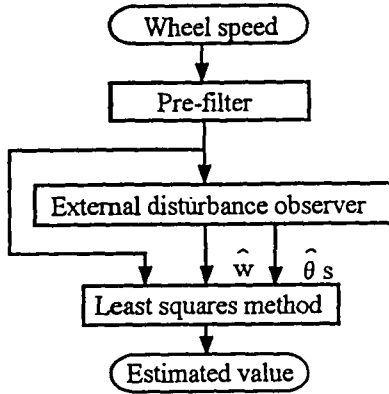


Fig. 5 Block Diagram of Air Pressure Estimation Method

### Estimation of External Disturbance

When the tire pressure changes, and the torsional spring constant  $K$  and the equivalent viscous damping coefficient  $D$  change as shown in Equation (2),

$$K \rightarrow K + \Delta K \quad D \rightarrow D + \Delta D \quad (2)$$

the equation of state for the tire becomes equivalent to the condition in which the external disturbance, as shown in Equation (4), is applied to the normal condition, as shown in Equation (3).

$$\begin{bmatrix} \dot{\omega}_1 \\ \dot{\omega}_2 \\ \dot{\theta}_s \end{bmatrix} = \begin{bmatrix} -D/J_1 & D/J_1 & -K/J_1 \\ D/J_2 & -D/J_2 & K/J_2 \\ 1 & -1 & 0 \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \theta_s \end{bmatrix} + \begin{bmatrix} 0 \\ -1/J_2 \\ 0 \end{bmatrix} T_d \quad (3)$$

$$w = \begin{bmatrix} 0 \\ -1/J_2 \\ 0 \end{bmatrix} T_d + \begin{bmatrix} -(\Delta K/J_1) \theta_s - (\Delta D/J_1) \theta'_s \\ (\Delta K/J_2) \theta_s + (\Delta D/J_2) \theta'_s \\ 0 \end{bmatrix} \quad (4)$$

Since only the data on  $\omega_1$  can be obtained,  $\omega_2$  which secondary factor is expressed in Equation (5) is estimated.

$$w_2/J_2 = -(T_d/J_2) + (\Delta K/J_2) \theta_s + (\Delta D/J_2) \theta'_s \quad (5)$$

When this external disturbance is included in the equation of state equation for the system to construct an observer of the least order, the estimated external disturbance can be expressed as Equation (6).

$$\begin{aligned} \hat{w}_2 &= -T_d + \Delta K \hat{\theta}_s + \Delta D \hat{\theta}'_s \\ &= [\Delta K \quad \Delta D] \begin{bmatrix} \hat{\theta}_s \\ \hat{\theta}'_s \end{bmatrix} - T_d \end{aligned} \quad (6)$$

Consequently, variations  $\Delta K$  and  $\Delta D$  are estimated by using the least-squares method.

### Improvement in Detection Accuracy

In this section, the problems and the countermeasures related with the use of the estimated (variation of) spring constant under the above algorithm on the actual vehicle, and part of the compensation logic, which has taken into consideration the use environment, will be introduced.

#### 1. Separation of Uniformity Noise

The estimated value was found to vary at high vehicle speeds and at a certain vehicle speed. This variation was caused by the variation component of the rotational period, appearing in the form of a variation in the wheel speed under the influence of the uniformity of tire and sensor rotor, being added to the coupled vibration of tire and suspension.

Since the problem lay in the oscillation of the rotational period of the tire, it was separated by learning compensation of the periodic component. Fig. 6 shows the results of the countermeasure.

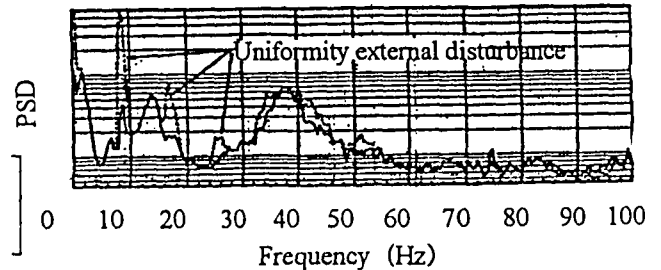


Fig. 6 PSD after Separation of Tire Uniformity

## 2. Compensation for Outside Air Temperature

Changes in the rubber hardness of the tire according to the temperature are shown in Fig. 7. Since the changes in the rubber hardness of the tire affect the spring constant in a certain temperature range, the estimated spring constant was compensated for by taking into consideration the temperature data.

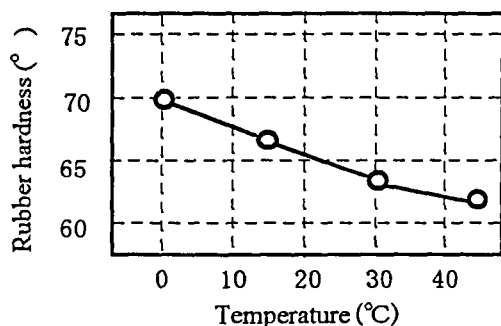


Fig. 7 Changes in Rubber Hardness According to Temperature

## System Configuration

Fig. 8 shows the system configuration and Fig. 9 shows the parts layout diagram. This system consists of a wheel-speed sensor that detects the rotational speed of four wheels, a temperature sensor that collects temperature data, a set switch that makes the system learn the initial setting for the timing of tire replacement, a computer that calculates to estimate the tire pressure based on the above signal and send outputs to the warning lamp, and a warning lamp in the meter that indicates the tire pressure loss.

If the computer is shared with other systems, the set switch and the warning lamp will be the only parts designed exclusively for this system.

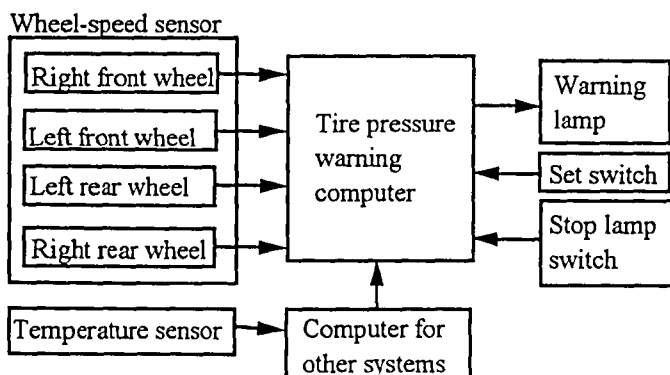


Fig. 8 System Configuration

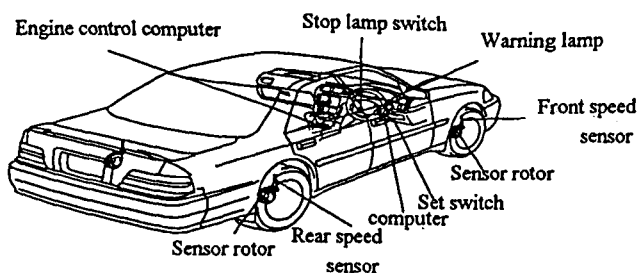


Fig. 9 Parts Layout Diagram

The design of the warning lamp is the one being applied to ISO (Fig. 10).

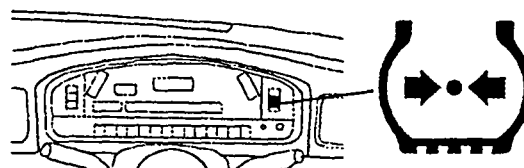


Fig. 10 Example of Warning Lamp

## System Performance on Actual Vehicles

Fig. 11 shows the results of the evaluation of a vehicle equipped with this system.

The test vehicle had the following specifications:

- Rear-wheel-drive vehicle
- 3.0-liter natural aspiration engine
- A/T
- Tire size: 205/65R15

The computer-output values of the test vehicle driven on the test course were evaluated at three levels of tire pressure.

It was found that the computer-output value fell as the tire pressure fell.

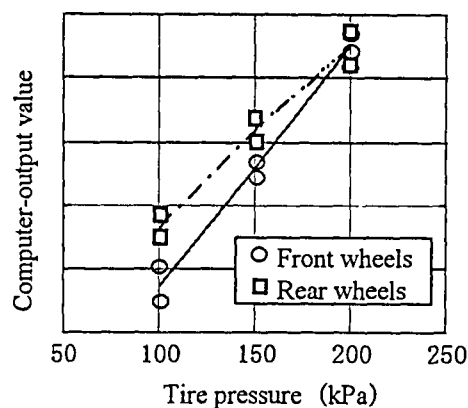


Fig. 11 FR Vehicle Road-Test Results (on Test Course)

Fig. 12 shows the results of the evaluation of another vehicle equipped with this system conducted outside the company.

The test vehicle had the following specifications:

- Front-wheel-drive vehicle
- 1.6-liter natural aspiration engine
- A/T
- Tire size: 185/65R14

Although the variation in the estimated value slightly increased for the general road driving because of variations in road surface conditions and running conditions, the system was confirmed to show adequate performance in practical uses with the addition of the above compensation logic.

In this system, the estimated value is updated every 60 seconds. In the event of a puncture caused by nail or other foreign objects on the tire, the time required for reduction in the tire pressure to the JATMA-specified minimum pressure of 140 kPa will be about 30 minutes, if the standard pressure is set at 200 kPa. Thus, the estimation time is considered to be practically sufficient.

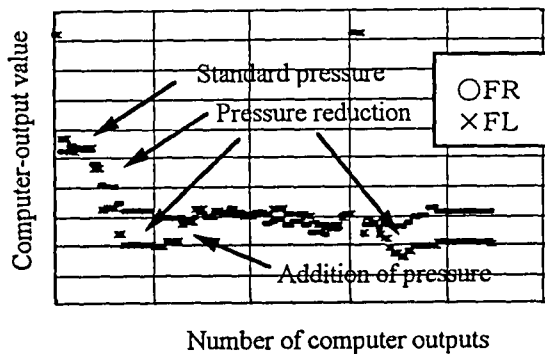


Fig. 12 FF Vehicle Exterior Road Test Results  
(approximately 2-hour driving)

## Conclusion

- By focusing on the correlation between the tire pressure and the spring constant of the tire, a system in which the variation in the spring constant of the tire was estimated on the basis of the wheel-speed sensor signal for each wheel by using the external disturbance observer.

- The system was developed at a low cost by using the existing wheel-speed sensor for ABS, and designed to detect the tire pressure loss of a single wheel as well as the simultaneous tire pressure loss on four wheels.

Finally, the authors wish to express a renewed feeling of gratitude to numerous people concerned in the development effort for their cooperation.

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## DEVELOPMENT OF THE BRAKE ASSIST SYSTEM

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Paper Number 98-S2-P-17

### ABSTRACT

Investigations and analyses of braking behavior of inexperienced drivers in emergency situations have shown that the Brake Assist System which determines an appropriate emergency braking operation and assists in applying the necessary braking force is effective in terms of active safety. While the system designed to detect an emergency braking operation and to consistently apply the maximum braking force is effective for those drivers who cannot apply sufficient braking effort, the system will make experienced drivers feel disagreeable because the system may work against their intention to control the vehicle. Consequently, we utilized an ABS actuator to develop a type of Brake Assist System with excellent control performance and less disagreement.

### INTRODUCTION

Inability of inexperienced drivers to apply sufficient braking effort in emergency situations was reported in various researches and analyses of their emergency braking behavior(1)(2)(3)(4). It was also found that a mere improvement in the braking performance did not produce the sufficient braking force in the emergency situation(5)(6). To overcome these problems, the Brake Assist System using a vacuum booster was developed as a system to detect an emergency braking operation and to assist in the addition of the braking force in such a situation(5)(6)(7)(8)(9). The authors have recently developed a hydraulic Brake Assist System by using a highly versatile ABS actuator(10)(11). This paper will characterize the emergency braking behavior of inexperienced drivers, and outline the control concept and the control procedure of the Brake Assist System.

#### Characteristics of Emergency Braking Operation

To investigate the braking behavior in emergency situations, inexperienced drivers, both male and female, in a wide range of age group from eighteen to seventy, were invited to a "training session for drivers" for an unannounced test consisting of an obstacle darting out in front of the car. To reproduce the tense atmosphere close to the reality, the connecting road within the test-driving course having the same environment as the city road and the suburban road was selected as the driving course for this experiment. The obstacle was abruptly thrown out in

front of the vehicle during while the driver was on its way to the site of the "training session" with relaxed feeling. The pedal effort versus time in emergency and normal situations are compared between the driver who could apply sufficient braking effort and the driver who could not, as a representative example of the test results in (Fig 1.). From this chart, the characteristics of the driver who could not apply sufficient braking effort were derived as follows:

- ① There was a significant difference in the initial pedal travel speed between normal and emergency situations, and the initial pedal travel speed in an emergency situation was the same for the driver who could apply sufficient braking effort and the driver who could not.
- ② The initial pedal effort of the driver who could not apply sufficient braking effort was not as strong as the driver who could, and the maximum pedal effort of the former was less than one-third of the latter.
- ③ The driver who could not apply sufficient braking effort tended to weaken the pedal effort during the braking operation.

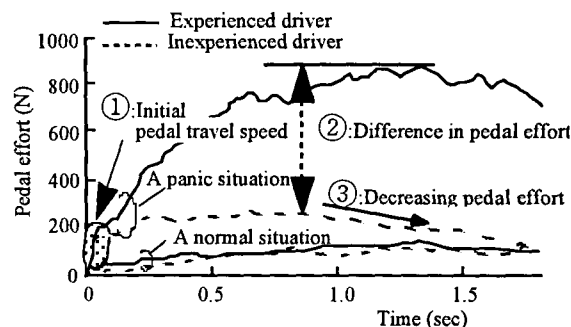


Fig 1. Comparison between in a panic and normal situation.

It was suggested in ① that an emergency braking could be detected by the initial pedal travel speed. Then brake pedal travel speeds and pedal strokes in the test results, under various driving conditions including normal braking operation were compared and sorted out as shown in (Fig 2.). These results indicated that an emergency braking could not be detected adequately by the pedal travel speed alone since the results overlapped with the braking operation during highway driving. However, it was found that an emergency braking can be detected by the travel speed and the pedal stroke.

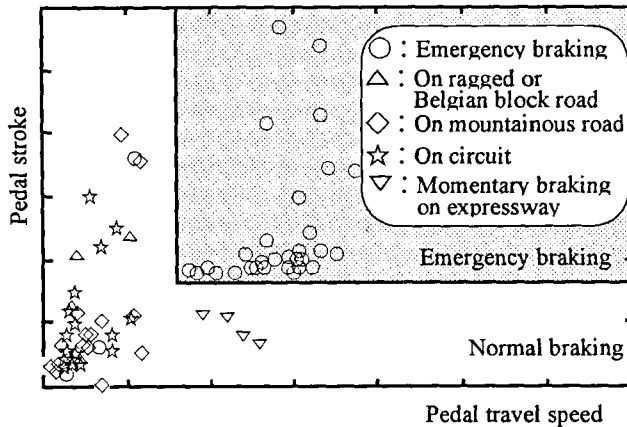


Fig 2. Results of investigation on pedal stroke.

### Control Concept

To help inexperienced drivers achieve the stopping distance of experienced drivers while taking into consideration the braking behavior of the driver who cannot apply sufficient braking effort in the emergency situation described above, an assistance in adding the braking force is needed. Thus, the following two control concepts were studied.

(A) The maximum braking force is applied whenever an emergency braking is detected.

(B) After providing assistance in adding a certain braking force, the braking force is controlled to reflect driver's intention.

While the concept (A) would be effective if the driver is not accustomed to applying sufficient braking effort, the experienced driver would feel disagreeable with the System since a certain maximum braking force would be applied without regard to the driver's intention of controlling the deceleration. Consequently, the range for detection of emergency braking had to be extremely limited, which would significantly compromise the advantage of the System. On the other hand, in the concept (B), owing to the control feature, the detection of an emergency braking would not be unnecessarily limited, would work to the advantage of a greater number of drivers, and would help drivers prevent traffic accident. Therefore, the development work was carried out according to the concept (B).

### System Configuration

This system is designed to provide assistance in applying the braking force by using an ABS pump. When the expected popularization of ABS in the future is taken into consideration, the system has the widest scope of application, and will be the mainstream system of the future in our opinion.

The system configuration is shown in (Fig 3.).

In this system, the fluid-pressure sensor for detecting an emergency braking, the fluid-pressure shut-off valve (SMC) for providing assistance in applying the braking force, and

the inlet valve (SRC) at the end of the pipe connected with the master reservoir were added to the conventional ABS including actuator control valve, pump and reservoir. The motor-driven ABS pump is activated to provide assistance in applying the braking force in excess of the actually-applied braking force.

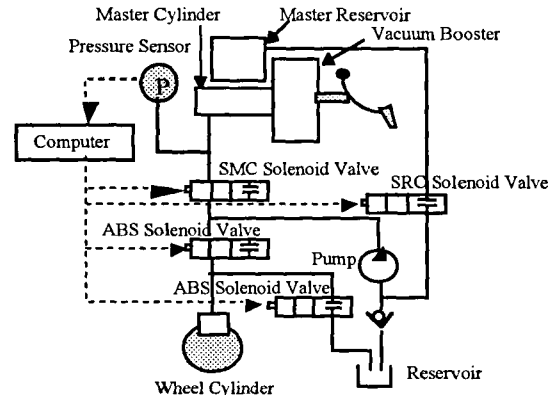


Fig 3. Hydraulic Brake Assist System configuration.

### Operating Pattern of the System

Although the control mechanism consisting of the detection of the start and end of control is considered sufficient to provide assistance in achieving the maximum braking force, an mechanism to control the braking force in the way the driver intended is necessary to make most drivers feel agreeable with the system. The basic operation of the system to achieve the controllability of the braking force is shown in (Fig 4.). It shows a change in the brake effectiveness (brake fluid pressure) in each control stage after the start of control. Each control stage (mode) is outlined below:

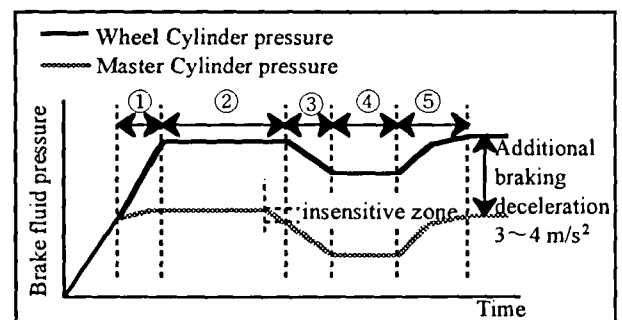


Fig 4. Pressure control pattern in a panic braking.

#### ① Start of pressure increasing mode

When an emergency braking is detected, the brake effectiveness is increased by applying a certain additional braking force by rotating the pump, closing the shut-off valve, and opening the inlet valve to take in

the brake fluid from the reservoir. The pressure increasing gradient is fixed in terms of the driving pattern of the inlet valve (Fig 5.).

## ②,④ Pressure retaining mode

When the driver maintains the pedal effort, the shut-off valve and the inlet valve are closed to maintain the amount of system-assisted braking force, and the intake of brake fluid from the reservoir is stopped, and the application of additional braking force is stopped (Fig 6.). The pump keeps rotating in consideration of the response of the pressure increasing control.

## ③ Pressure decreasing mode

When the brake pedal is relaxed, the inlet valve is closed, and the shut-off valve is opened to return the brake fluid to the master cylinder in order to reduce the system-assisted braking force. To emphasize the controllability of the system, the deceleration decreasing gradient is controlled according to the pedal release speed (the brake fluid pressure sensor decreasing gradient), and the reduction in deceleration is controlled according to the pedal release (the decreasing amount of the brake fluid pressure sensor value). By controlling the decreasing gradient of deceleration and the reduction in deceleration in this way, the system intends to have the driver's intention reflected in the actual deceleration. The pressure decreasing gradient is fixed in terms of the driving pattern of the shut-off valve (Fig 7.). However, since inexperienced drivers tend to unintentionally reduce the pedal effort in an emergency braking operation, the system is designed with the insensitive zone to slow the decrease in the system-assisted braking force when the foot pressure on the brake pedal is slowly reduced.

## ⑤ Pressure increasing mode

When the foot pressure on the brake pedal is increased again, the system emphasizes the controllability feature by controlling the deceleration increasing gradient according to the pedal travel speed (the brake fluid pressure sensor increasing gradient), and the increase in deceleration according to the additional pedal effort (the increasing amount of the brake fluid pressure sensor value). By controlling the increasing gradient of deceleration and the increase in deceleration in this way, the system intends to have the driver's intention reflected in the actual deceleration (Fig 5.).

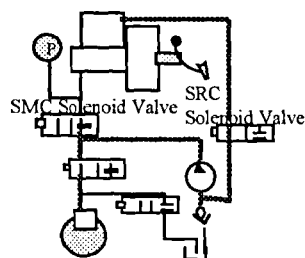


Fig 5. Pressure-increasing mode.

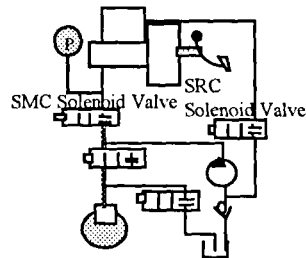


Fig 6. Pressure-retaining mode.

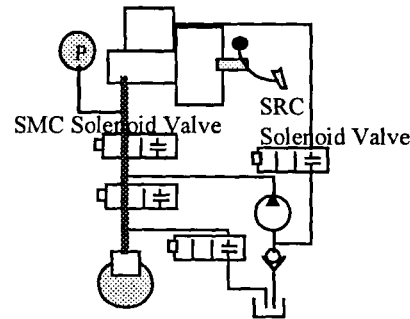


Fig 7. Pressure-decreasing mode.

## Key Points in Control Mechanism

To achieve the operation of the control mechanism without making the driver hold unnatural feeling, the following points were taken into consideration in the development of the system.

### Setting of Appropriate Start-of-Control Timing -

If the control mechanism is switched on too soon after the detection of an emergency braking, the system will not achieve the intended effect, and activation of the control mechanism may even be considered unnecessary for the driver who can apply sufficient braking effort. If the control mechanism is switched on too late, deceleration will be rather bumpy and uncomfortable (See Fig. 8). Thus, the start-of-control was appropriately timed by switching on the control mechanism when the master cylinder fluid pressure gradient (the driver's pedal travel speed) has decreased to a certain level.

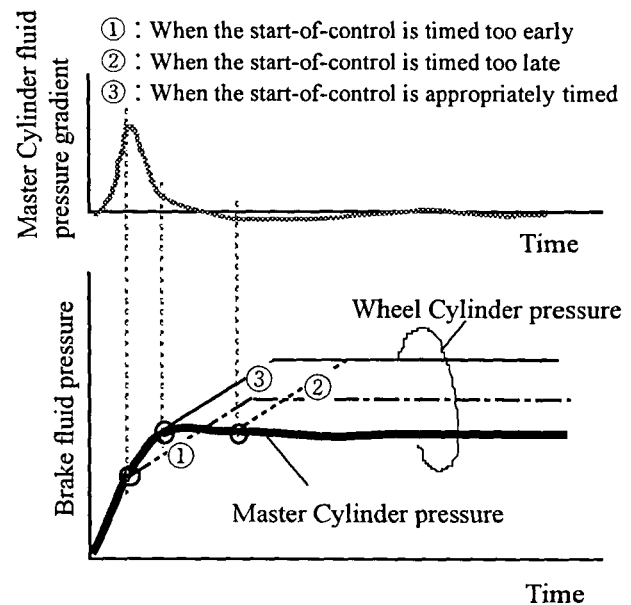


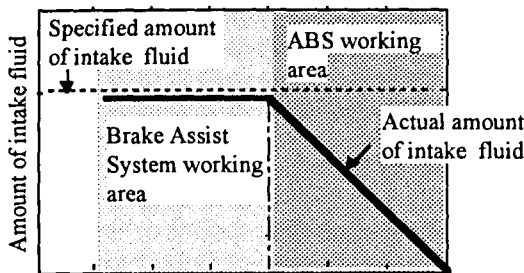
Fig 8. Waveform of controlled fluid pressure under different start-of-control timings

**Achievement of Optimum Amount of Additional Braking Force** - According to body sensing, the initial amount of additional braking force at 3-4 m/s<sup>2</sup> in deceleration seemed appropriate. Then, the intake time (T) from the reservoir necessary for the specified amount of additional braking force was determined from the following equation:

$$T = Q / K \times P \times G \quad (1.)$$

where, Q : The amount of fluid necessary for an increase of the unit fluid pressure in the wheel cylinder (in cc/MPa); K : Delivery capacity of the pump (in cc/s); P: The fluid pressure of the wheel cylinder necessary to increase the unit deceleration as determined by the vehicle specification (in MPa/m/s<sup>2</sup>); G : Specified system-assisted deceleration (in m/s<sup>2</sup>)

**Pedal Feeling without Disagreement** - In this system, the relationship between the pedal stroke and the fluid pressure changes to feed the brake fluid in the reservoir into the brake system. Thus, in the range of pedal effort where the specified amount of intake fluid will sufficiently activate ABS, the amount of intake fluid is estimated from the intake time, and determined so that the intake brake fluid is guarded by the maximum possible deceleration on a dry asphalt road (Fig 9.). In other words, the amount of system-assisted braking force is determined on a map so that the intake amount is decreased as the master cylinder fluid pressure at the start of control is increased. As a result, the system achieved the pedal feeling with little disagreement during the operation of the control mechanism under various road conditions.



Master Cylinder pressure at the start of control

Fig 9. Intake fluid amount control map.

### Effectiveness of the System

The relationships between the pedal effort and the deceleration of the vehicle with and without the Brake Assist System are shown in Fig. 10. The chart indicates an additional deceleration of about 3 m/s<sup>2</sup> until the pedal effort reaches 160 N. The deceleration remained constant from that point on because the deceleration did not increase due to its dependence on the coefficient of friction of the road surface.

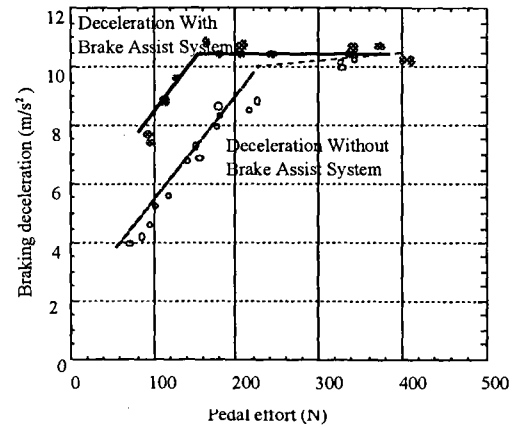


Fig 10. Comparison of braking deceleration between cases with and without Brake Assist System

(Fig 11.) compares the braking distances in the cases of ordinary drivers in emergency braking situations with and without the Brake Assist System. The Brake Assist System was proven effective as the braking distance with the Brake Assist System was shorter than the distance without the Brake Assist System. Since the Brake Assist System did not produce better results for experienced drivers who could stop in a short distance without the System, the System cannot be expected to prove its effects for experienced drivers. Nonetheless, the System will not impair the braking performance of the vehicle.

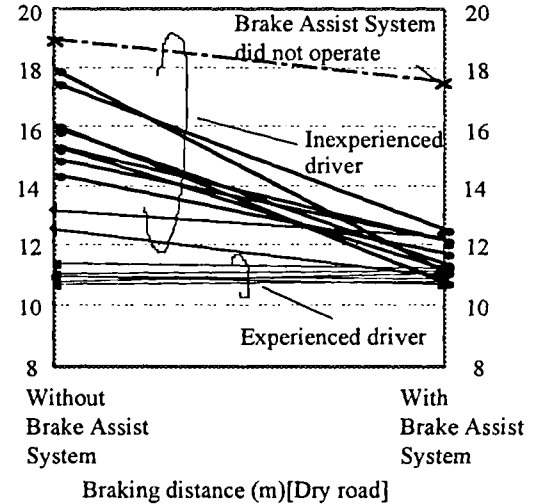


Fig 11. Comparison of braking distance between cases with and without Brake Assist System

### CONCLUSION

The investigation and the analysis of the emergency braking behavior of inexperienced drivers demonstrated that an emergency braking is detectable. Controllability was the key factor in this system, and a system based on the



brake fluid pressure sensor and the ABS actuator was developed. The newly-developed system showed that it was capable of assisting inexperienced drivers in the braking operation, and producing the braking performance achieved by experienced drivers. While the conventional ABS, traction control system (TRC) and vehicle stability control system (VSC) are the technologies designed to assist the driver by expanding the vehicle stability range, the Brake Assist System is a new type of active safety technology aiming to allow every driver to have a complete command of vehicle's performance. However, the system is by no means capable of exceeding the physical limits. Therefore, it is another goal of ours to make inexperienced drivers more aware of traffic safety without placing too much confidence on the Brake Assist System.

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# A TEST TRACK PERFORMANCE EVALUATION OF CURRENT PRODUCTION LIGHT VEHICLE ANTILOCK BRAKE SYSTEMS

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## ABSTRACT

*A Test Track Performance Evaluation of Current Production Light Vehicle Antilock Brake Systems* was conducted to compare the braking performance of vehicles equipped with present-day antilock brake systems (ABS) with the performance of the same vehicle without ABS (simulated conventional brakes) over a large range of driving conditions. The motivation for this work was to attempt to find situations and/or conditions in which ABS-equipped vehicles did not perform as well as their non-ABS counterparts, not to compare vehicles or antilock brake systems to one another.

The braking performance of nine high production passenger vehicles was evaluated in seventeen stopping situations. These situations were comprised of various road surfaces, driver steering actions, and vehicle speeds. Testing was performed with lightly and heavily laden vehicles, with the ABS active and disabled, and used two brake pedal application techniques. The selected vehicles included at least one ABS from eight current ABS manufacturers.

This study found that for most stopping maneuvers on most surfaces, ABS-assisted full pedal brake application stops were shorter than those made with the ABS disabled. Additionally, vehicular stability during these maneuvers was almost always superior with the assistance of ABS. The one systematic exception was on loose gravel where stopping distances increased by an average of 27.2 percent overall.

## INTRODUCTION

Antilock brake systems (ABS) first appeared in the U.S. during the late 1960's. By the late-80's four-wheel ABS had become standard equipment on a limited number of sport and luxury-oriented automobiles and light trucks. In recent years, ABS has become more

common and is now standard equipment on many high production passenger cars and light trucks. According to ITT Automotive, 62 percent of 1996 model year vehicles were equipped ABS [1].

The principal reason for equipping passenger cars and light trucks with ABS is to increase safety. Years of watching the enhanced lateral stability and improved stopping performance of vehicles equipped with ABS on the test track initially convinced brake experts that the widespread introduction of ABS should significantly reduce the number of crashes, and the resulting injuries and fatalities, that occur on our nation's highways.

To determine whether the experts' belief that the introduction of ABS would increase safety was indeed true, a number of statistical analyses of crash databases have been performed over the past several years. These analyses suggest that, for automobiles, the introduction of ABS has produced net safety benefits much lower than originally expected for ABS-equipped vehicles [2,3,4,5]. For example, Kahane found that while the involvement of ABS-equipped automobiles in fatal multi-vehicle crashes on wet roads was reduced by 24 percent, fatal single vehicle crashes increased by 28 percent [5]. This increase in single-vehicle crashes almost completely offsets the safety advantage an ABS-equipped automobile has over its conventionally-braked counterpart. Similar results were found in the other automobile crash database studies. Note that the anticipated safety benefits due to ABS *were* seen in light truck (rear wheel ABS only) crash data studies.

To learn why the crash data studies did not find the anticipated increase in safety for ABS-equipped automobiles, the National Highway Traffic Safety Administration (NHTSA) developed its Light Vehicle ABS Research Program. This comprehensive program attempts, in a series of tasks, to examine all plausible reasons why the crash data studies do not show that ABS has improved automobile safety. NHTSA's

Motor Vehicle Safety Research Advisory Committee's (MVSRA) ABS Working Group, comprised of government and industry participants, commented on, and approved of, the research program's test plan. The group's contribution is much appreciated.

## BACKGROUND AND STUDY OBJECTIVES

*A Test Track Performance Evaluation of Current Production Light Vehicle Antilock Brake Systems* (Task 4 of the eight NHTSA Light Vehicle ABS Research Program tasks) was conducted to compare the braking performance of vehicles equipped with present-day antilock brake systems to the performance of the same vehicle without ABS over a large range of driving conditions. The braking performance of nine vehicles, each equipped with a different manufacturer's ABS, was evaluated in seventeen stopping situations involving a variety of road surfaces, driver steering actions, and vehicle speeds. Testing was performed with lightly and heavily laden vehicles and with the ABS active and disabled.

The motivation for this work was to attempt to find situations and/or conditions in which vehicles equipped with ABS would not perform as well as their non-ABS (conventionally braked) counterparts. While ABS stopping performance has been measured by many groups over many years, there is a possibility that poor performance on some unusual surface or during some maneuver may have been overlooked. If such conditions could be found, they may explain the apparent increase in single-vehicle crashes of ABS-equipped automobiles. Note that it was not the intention of this work to compare vehicles or antilock brake systems to one another.

ABS performance evaluations have been conducted prior to this study by NHTSA's Vehicle Research and Test Center (VRTC) in East Liberty, Ohio [7,8]. In these earlier evaluations, a number of vehicles equipped with a variety of antilock brake systems were tested over a range of road surfaces and stopping maneuvers. Both of these earlier studies found that ABS improved vehicular stability under braking, especially when a difference in road friction coefficients existed between the left and right sides of the vehicle. Four-wheel antilock brake systems reduced the tendency of the vehicles to yaw excessively and allowed the driver to maintain steering control while braking. Rear-wheel-only ABS was found to only enhance braking stability, as these systems are not designed to modulate the longitudinal slip of the front wheels during braking. Therefore, although rear-wheel-

only ABS prevented excessive yaw, no steering control benefits were provided to the driver during braking.

The earlier studies also found that stopping distances on hard, paved test surfaces either stayed the same or were reduced for four-wheel ABS-equipped vehicles. Stopping distance increases of over 25 percent occurred in several cases on gravel. In some cases rear-wheel ABS slightly reduced stopping distances and, in other cases, increased it.

The current ABS performance evaluation differs from those previously performed by VRTC in several significant ways. First, the vehicles tested have newer antilock brake systems than those tested in the earlier studies. Second, the vehicles were tested on more surfaces than in the past. Third, the vehicles were tested on a number of surfaces having sudden coefficient of friction transitions (past VRTC testing has found that some antilock brake systems have problems dealing with such transitions). Fourth, the vehicles were tested in additional maneuvers. Again, past VRTC testing found that some systems exhibited braking deficiencies while performing certain maneuvers (e.g., hard braking while in a curve).

## TEST PROCEDURE

### Test Vehicles

The test vehicle fleet included a diverse range of high production passenger vehicles, ranging from compact cars to sport utility vehicles. The selected vehicles included at least one ABS from eight current ABS manufacturers.

Eight vehicles were equipped with "add-on" ABS packages, and one was "integrated." Although the functionality of these configurations is identical, the integrated ABS physically combines the master cylinder with the hydraulic control unit (HCU) into one component. The master cylinder and HCU of the add-on systems, however, are joined only by the brake lines run between them.

The antilock brake systems in seven of the nine test vehicles used four wheel speed sensors, one at each wheel. The two rear-wheel drive vehicles utilized three wheel speed sensors, one positioned at each front wheel and one in the rear differential. Four vehicles were equipped with four-channel antilock brake systems that independently modulated the front and rear brake line pressures at each wheel. The five remaining test vehicles were equipped with three-channel antilock brake systems that also modulated the two front line pressures independently, but modulated

the line pressures at the right rear and left rear together. The ABS configurations of each test vehicle are listed in Table 1.

**Table 1.**  
**Test Vehicle ABS Configuration**

Vehicle	ABS Configuration
A	add-on; four-sensor, four-channel
B	integrated; four-sensor, four-channel
C	add-on; four-sensor, four-channel
D	add-on; four-sensor, three-channel
E	add-on; four-sensor, four-channel
F	add-on; four-sensor, three-channel
G	add-on; four-sensor, three-channel
H	add-on; three-sensor, three-channel
I	add-on; three-sensor, three-channel

It should be noted that this study originally included only eight test vehicles. However, as the eighth vehicle was approaching test completion, seemingly odd ABS behavior was noted in a vehicle being driven in another NHTSA test program. When a large braking input was applied during the program's steer-and-brake maneuver, the brake pedal would rise quickly and remain firm against the driver's foot (due to ABS activation) at high lateral acceleration. Although this is not necessarily a negative feature, the pedal rise also coincided with the sensation that the vehicle was not generating the anticipated braking force and vehicle deceleration.

Preliminary braking maneuvers were conducted and confirmed the previously noted pedal feel and perceived stopping distance increase whenever a high lateral acceleration was established prior to a large brake pedal force input. Such behavior was not observed in the eight vehicles of the original test matrix. Recalling that the motivation for this study was to find situations where the use of ABS resulted in some form of stopping deficiency (when compared to the same vehicle equipped with conventional brakes), it was determined that the vehicle should be subjected to the entire ABS hardware evaluation test matrix as a ninth vehicle.

## Instrumentation

Table 2 provides a list of instrumentation installed in each test vehicle. The fifth wheel assembly was mounted to the rear bumper attachment points and transmitted vehicle speed and distance signals to a digital performance monitor positioned on the dashboard. The monitor's trigger input was activated by the brake light switch to freeze the initial vehicle speed and zero vehicle position when the brake pedal was depressed. The speed and position measured by the fifth wheel were recorded as a function of time with an update rate of 100 Hz by a digital on-board data acquisition system.

Brake line pressure transducers were connected between the hard and flexible brake lines to transmit the line pressure seen at each wheel downstream of the ABS HCU. Direct current tachometers attached to each wheel monitored wheel lockup by measuring individual wheel speeds. A load cell was attached to the brake pedal to transmit applied force. Two accelerometers and a rate sensor, positioned at the vehicle's center of gravity to minimize vehicle pitch and roll effects, measured lateral/longitudinal acceleration and yaw rate, respectively. To signal a desired point within a braking maneuver, an optical pickup sensor was installed on the vehicle's front license plate bracket. All data measured by this instrumentation were recorded, as a function of time, by the on-board data acquisition and each channel was sampled at a rate of 100 Hz.

## Loading

Each vehicle was tested at two loading conditions: lightly laden and at its Gross Vehicle Weight Rating (GVWR). Lightly laden was defined as the vehicle curb weight (with a full tank of fuel) plus the test driver and instrumentation. The GVWR condition involved loading the vehicle to the maximum vehicle weight recommended by the manufacturer, and was achieved by ballasting the test vehicle with sand bags distributed so that the axle weights were in proportion with the Gross Axle Weight Ratings (GAWR).

## Test Matrix

Table 3 summarizes this study's test matrix. Testing was performed with ABS and with the ABS disabled using two pedal application techniques. The matrix included nine different test surfaces and five

different stopping maneuvers, each performed with the vehicles lightly laden and at GVWR. To disable the ABS, an electrical fuse in the test vehicle's fuse box

was replaced with a fused toggle switch to interrupt power to the ABS electronic control unit, solenoid valves, or pump motor.

**Table 2.**  
**Instrumentation**

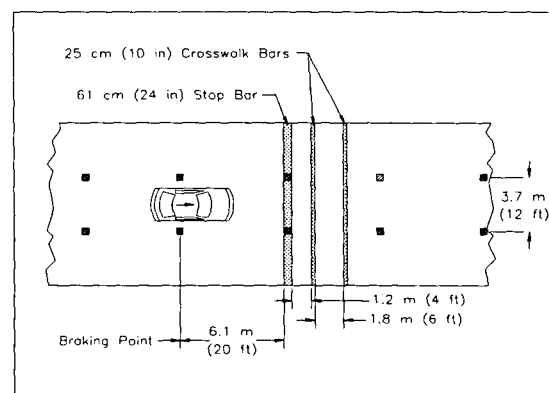
Description	Measured Data	Vehicle Location
Accelerometer	Lateral and longitudinal acceleration	Positioned at center of gravity
Fifth wheel	Vehicle speed and distance traveled	Rear bumper attachment points
Load cell	Brake pedal force	Brake pedal
Pressure transducers	Brake line pressure seen at each caliper or drum	Between hard and flexible brake lines at each corner
Rate sensor	Yaw rate	Positioned at center of gravity
Optical pickup sensor	Event trigger	Front license plate bracket
Wheel tachometers	Individual wheel speed	Each wheel via wheel mounting lugs or lug nuts

### Test Surfaces

Nine surface types were used for this study: dry asphalt, wet asphalt, dry concrete, wet polished concrete, wet epoxy, grass, loose gravel, wet Jennite, and an epoxy/sand surface. The polished concrete was designed to simulate a heavily worn road and was created by troweling and polishing with a floor polisher. The epoxy pad (asphalt covered with a coating typically used on factory floors) and wet Jennite (a coal tar emulsion asphalt sealer trade name) surfaces simulated badly worn wet roadways. Due to severe deterioration, the epoxy pad was resurfaced before the final two vehicles were evaluated, reducing the peak coefficient of friction and slide skid numbers by over one third.

This study also utilized a specially designed ABS test course. Created in mid 1996, the course was designed to evaluate ABS performance on a series of simulated real world test pads. An antilock brake system's ability to recover vehicle deceleration after returning to smooth asphalt from a given pad were observed. Each of the four ABS test course pads were wet during testing. Test Pad #0 was used to determine vehicle stopping distance for the wet, unperturbed asphalt surface of the course. Test Pad #1 included one Jennite strip 61 cm (24 in) wide applied to the asphalt to simulate a stop bar found at an intersection with a stop sign or traffic light. Test Pad #2 (Figure 1)

simulated a stop bar followed by two bars to mark crosswalk area, and was oriented as follows: a 61 cm (24 in) wide Jennite stop bar, four feet of asphalt, a 25 cm (10 in) Jennite strip, six feet of asphalt, and a second 25 cm (10 in) Jennite strip. Test Pad #3 (Figure 2) consisted of two adjacent artificial potholes, one in each wheel track, constructed from steel frames set into concrete and treated with an epoxy/sand surface. The wet epoxy/sand surface provided a coefficient of friction very similar to dry pavement.

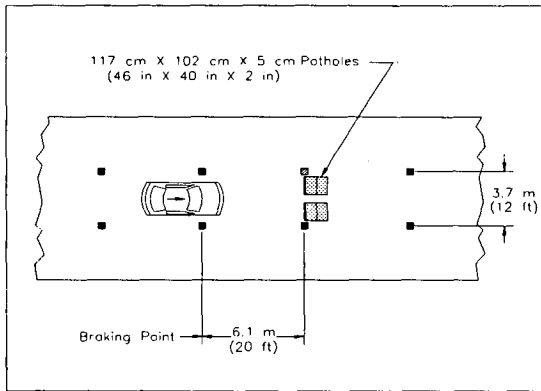


**Figure 1. ABS Test Pad #2.**

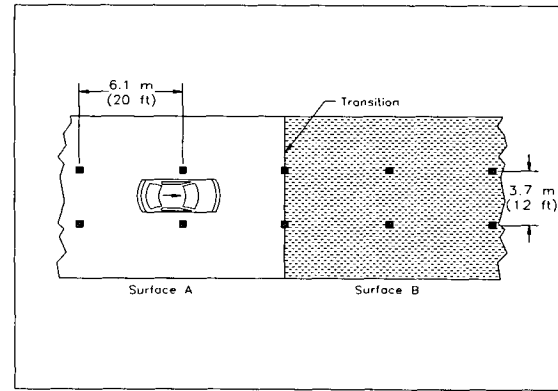
**Table 3.  
Light Vehicle ABS Test Matrix**

<b>Surface</b>	<b>Nominal ASTM Skid No. (Peak/Slide)</b>	<b>Maneuver</b>	<b>Speed</b>
Dry Concrete	90/75	Straight Line	97 km/h (60 mph)
Wet Polished Concrete	unknown/60	Straight Line	64 km/h (40 mph)
Wet Asphalt	85/65	Straight Line	80 km/h (50 mph)
Wet Jennite	30/10	Straight Line	64 km/h (40 mph)
Grass	unknown	Straight Line	40 km/h (25 mph)
Loose gravel	unknown	Straight Line	56 km/h (35 mph)
Wet Asphalt to Wet Jennite	(85/65) to (30/10)	Transition	64 km/h (40 mph) Transition at 40 km/h (25 mph)
Wet Jennite to Wet Asphalt	(30/10) to (85/65)	Transition	56 km/h (35 mph) Transition at 40 km/h (25 mph)
Wet Asphalt across corner of Wet Epoxy to Wet Asphalt	(85/65) across corner of (20/3)* to (85/65)	Transition	64 km/h (40 mph) Transition at 40 km/h (25 mph)
ABS Test Pad #0	85/65	Transition	64 km/h (40 mph)
ABS Test Pad #1	(85/65) to (30/10) to (85/65)	Transition	64 km/h (40 mph)
ABS Test Pad #2	(85/65) to (30/10) to (85/65)to (30/10) to (85/65)to (30/10) to (85/65)	Transition	64 km/h (40 mph)
ABS Test Pad #3	(85/65) to unknown to (85/65)	Transition	64 km/h (40 mph)
Wet Asphalt/Wet Epoxy	(85/65) / (20/3)*	Split-Mu	48 km/h (30 mph)
Dry Asphalt	90/80	Curve (91.4 m radius)	80 km/h (50 mph)
Wet Jennite	30/10	Curve (152.4 m radius)	64 km/h (40 mph)
Dry Asphalt	90/80	J-turn	80 km/h (50 mph)

\* The actual skid numbers of the epoxy surface exceeded the nominal specifications for the first seven test vehicles. The average peak and slide values recorded during this time interval were 52 and 14, respectively.



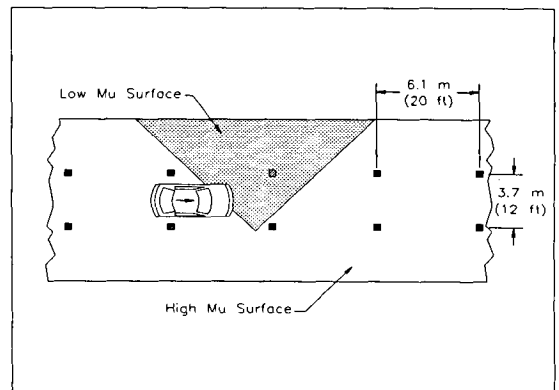
**Figure 2. ABS Test Pad #3.**



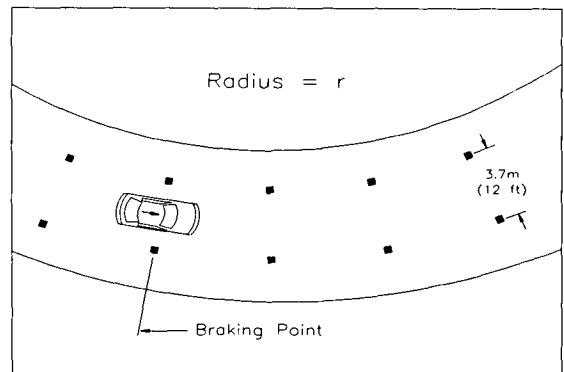
**Figure 3. Perpendicular transition.**

### Maneuvers

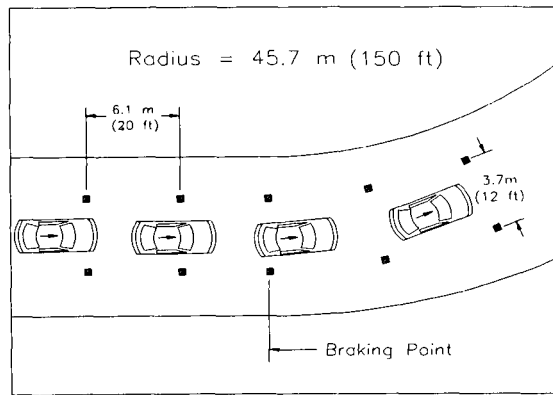
This study involved five stopping maneuvers: 1) straight line, 2) split-mu, 3) transition, 4) curve, and 5) J turn. Straight line maneuvers involved stopping on a uniform coefficient surface. Split-mu maneuvers required straight line stopping over a surface with split (side-to-side) frictional coefficients. Transition maneuvers (Figures 3 and 4) were made while the driver applied a constant brake application as the vehicle traveled over surfaces with changing frictional coefficients. The initial speed and brake application points were chosen such that the initial surface transition would be accomplished at approximately 40 km/h (25 mph). Braking in a curve of known radius (Figure 5) and the J-turn, a maneuver designed to observe how a vehicle responded to a sudden and severe steering input quickly followed by a brake application (Figure 6), each occurred on surfaces with uniform frictional coefficients. All stopping lanes were 3.7 m (12 ft) wide, marked with cones spaced 6.1 m (20 ft) apart. For each maneuver, the test driver was allowed to make steering inputs as necessary to maintain lane position.



**Figure 4. Offset transition.**



**Figure 5. Braking in a turn.**



**Figure 6. J-turn maneuver.**

### Speed

The target speeds specified for each maneuver were chosen to reflect available space, real world utility, and safety considerations. Although these speeds are listed in Table 3, the actual speeds observed while testing varied slightly. As a result, the actual stopping distances were adjusted to represent the distances of those maneuvers as if they had been run at the target speed using the following expression [12]:

$$s' = \frac{v_{target}^2}{v_{actual}^2} \times s_{actual}$$

where

$$\begin{aligned} s' &= \text{corrected stopping distance} \\ v_{target} &= \text{target initial vehicle velocity} \\ v_{actual} &= \text{actual initial vehicle velocity} \\ s_{actual} &= \text{actual stopping distance} \end{aligned}$$

### Brake Applications

Two brake application techniques were used in this study: 1) "panic" and 2) "best effort." Panic applications involved a rapid force application of over 667 N (150 lbs) to the brake pedal. These stops were expected to be very repeatable, therefore only three panic stops for each case (ABS and disabled ABS) were conducted. Best effort stops required the driver to modulate pedal effort as necessary to achieve the

shortest possible stopping distance while maintaining vehicle control and lane position. No more than one wheel per axle was permitted to lock during best effort stops to ensure vehicular stability was maintained. To allow time for driver familiarization with a given vehicle's braking ability, six best effort stops were run for the maneuvers that required them. To eliminate driver variability effects, only one professional test driver with 17 years experience served as driver for all testing conducted for this study.

With the exception of the transitional stops on the ABS test course, each transition maneuver only included three ABS-assisted stops. Transitional maneuvers were designed to evaluate ABS reaction times and responses to sudden changes in roadway frictional coefficients. For this reason, it was unnecessary for disabled ABS stops to be conducted.

Best effort stops with the ABS disabled were not performed over the ABS test course transitions. Three disabled ABS panic stops, however, were included to facilitate an ABS stopping performance comparison.

Three ABS and three disabled ABS panic stops were tested on the grass and loose gravel surfaces. Data collected from best effort stops made on these surfaces was assumed to have few significant real world applications. Best effort stops, therefore, were deemed unnecessary on grass and gravel.

Braking in a curve and J-turn maneuvers did not require panic stops with the ABS disabled as it was expected that the vehicles would quickly lock their front wheels and skid out of the intended lane. Disabled ABS panic stops were likewise omitted from wet asphalt, dry asphalt, wet polished concrete, and dry concrete maneuvers due to the excessive tire wear executing such stops was expected to incur. For these seven maneuvers only three ABS-assisted and six best effort disabled ABS stops were conducted.

### TEST TRACK RESULTS

#### Comments on the Reporting of ABS Performance Results

The results reported in this section used stopping distance and vehicle stability as measures of braking performance. A vehicle yawing out of control with its wheels locked may stop in a very short distance, while a stable vehicle (its directional control maintained throughout the duration of the stop) may require a very long distance to complete its stop. Each condition presents different safety concerns and demonstrates why stopping distance and directional stability must be



evaluated together when discussing ABS performance.

A number of charts provide stopping distances observed with fully laden test vehicles in this section of the report. If a legend is not included with a given chart, the reported stopping distances were collected using ABS-assisted panic brake applications. If a legend is provided, “ABS” refers to an ABS-assisted panic stop, “Full Pedal” refers to a panic stop with the ABS disabled, and “Best Effort” refers to test driver modulated stops made with the ABS disabled.

Thirteen of the eighteen stopping maneuvers required ABS-assisted stopping distances to be compared to those measured with the ABS disabled. To facilitate this comparison, the following equation was used:

*ABS Stopping Distance Improvement=*

$$\frac{SD_{ABS\ disabled} - SD_{ABS}}{SD_{ABS\ disabled}} \times 100\%$$

where

$SD_{ABS\ disabled}$  = stopping distance achieved with an ABS disabled (panic or best effort)

$SD_{ABS}$  = stopping distance achieved with the assistance of an ABS

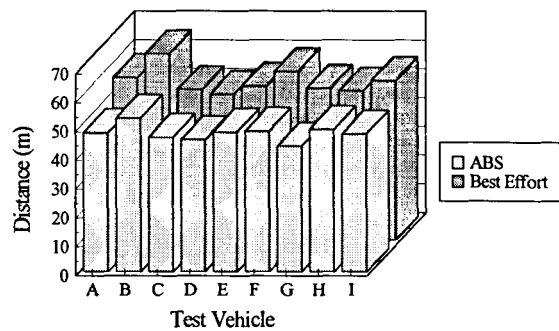
Although the ninth test vehicle was to be subjected to the complete ABS test matrix, an unforeseen event occurred during the single lane change maneuver that prohibited the completion of lightly laden testing. For this reason, many charts for this loading condition include stopping distances for eight vehicles only.

### Straight Line Stops on Uniform Coefficient Surfaces

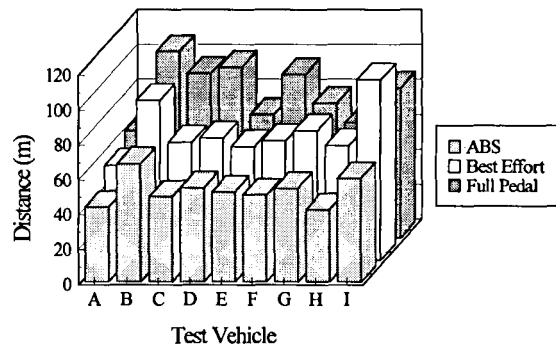
A panic brake application used in conjunction with ABS resulted in the shortest straight line stopping distances on the dry concrete and wet polished concrete surfaces for each of the eight test vehicles at both loading conditions (Figure 7 summarizes the GVWR stopping distances made on dry concrete). Antilock brakes also facilitated the shortest stopping distances on the wet Jennite (Figure 8) and wet asphalt surfaces for each vehicle when fully laden.

On wet asphalt, for the lightly laden loading condition, eight of the nine vehicles stopped in the shortest distance with ABS. The test driver’s minimum best effort stopping distances were 4.9 percent less than the ABS-assisted stops with vehicle “H” on wet

asphalt. On wet Jennite, for the lightly laden loading condition, seven of the eight vehicles stopped in the shortest distance with ABS. The test driver’s minimum best effort stopping distances were 9.2 percent less than the ABS-assisted stops with vehicle “A” on wet Jennite. Lightly laden straight line stops on wet Jennite were not performed with test vehicle “I”.



**Figure 7. Straight line stopping distances observed on dry concrete. Test vehicles were fully laden to their respective GVWRs.**



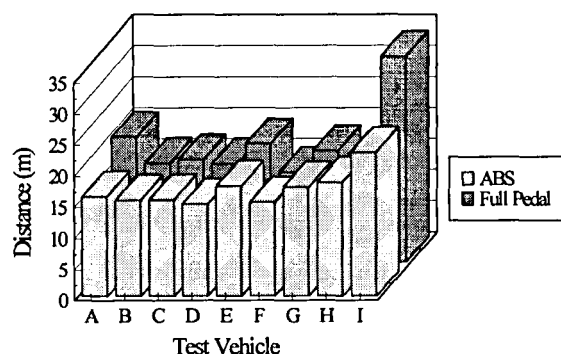
**Figure 8. Straight line stopping distances observed on wet Jennite. Test vehicles were fully laden to their respective GVWRs.**

### Straight Line Stops on Off-road Surfaces

**Grass** - Seven of the nine test vehicles laden to GVWR stopped in the shortest distance when a panic brake application was used in conjunction with ABS on the grass surface (Figure 9). The ABS-assisted stops were an average of 6.9 percent shorter than those made with the ABS disabled at GVWR. This percentage

drops to 4.0 percent if the stopping distances of vehicle "I" are not included in this comparison. Unlike for the other vehicles, the grass surface was very wet when test vehicle "I" was evaluated, and in some areas standing water was present. This may explain the 30.1 percent longer full pedal application stopping distance with the ABS disabled, when compared to the distance recorded with the assistance of ABS.

Conversely, six of the eight test vehicles stopped in the shortest distance with a panic brake application and disabled ABS when lightly laden. At this loading condition the stopping distances were an average of 7.1 percent longer than the ABS-assisted stops across the eight vehicle test group. Test vehicle "I" was not tested



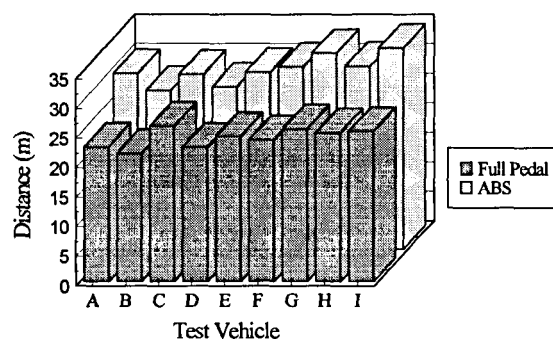
**Figure 9.** Straight line stopping distances observed on grass. Test vehicles were fully laden to their respective GVWRs. Note: the grass was very wet when the braking performance of vehicle "I" was evaluated.

on the grass when lightly laden.

**Loose Gravel** - On loose gravel, each of the nine vehicles stopped in the shortest distance with a panic brake application and disabled ABS, regardless of loading condition. Stops made on the gravel were lengthened considerably when the ABS was active: 24.6 percent when the test vehicles were fully laden (Figure 10) and 30.0 percent when lightly laden. The fully laden percentage drops to 23.4 percent if the stopping distances of vehicle "I" are not included in this comparison. As with the grass surface, the gravel was very wet when test vehicle "I" was evaluated, unlike for the other vehicles. This may explain the 33.7 percent stopping distance increase with ABS when compared to the distance observed with the ABS disabled.

The ABS-induced stopping distance increase may be best explained by examining the tire-to-roadway

surface interaction during the braking maneuver. It is generally accepted that the plowing of a vehicle's tires into a deformable surface such as loose gravel generates greater stopping forces than if the wheels were allowed to continue to roll over the surface (as in an ABS-assisted stop). Stopping distances made over the gravel surface therefore represent an inherent ABS design compromise. To preserve the driver's ability to maintain directional control of the vehicle while braking, the wheels must not be allowed to lock. By preserving this control, however, stopping distances made over the loose gravel test surface were extended.

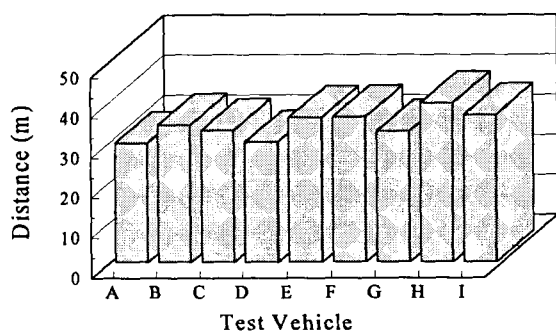


**Figure 10.** Straight line stopping distances observed on loose gravel. Test vehicles were fully laden to their respective GVWRs. Note: the gravel was wet when the braking performance of vehicle "I" was evaluated.

## Transition Surface Braking

The transitional stopping maneuvers were designed to detect gross deficiencies in ABS performance through the observation of unusually long stopping distances and vehicle instability. For each of the nine vehicles, evaluated over three transitions, no apparent shortcomings were revealed. Figure 11 presents typical results. This figure, shows the stopping distances recorded on the wet asphalt/wet Jennite transition surface for the test vehicles at their respective GVWRs. **ABS Test Course Braking**

Each of the nine test vehicles, under both loading conditions, stopped in the shortest distance when the test driver utilized a panic brake application with ABS on Test Pad #0, #1, and #2. On Test Pad #3, eight vehicles stopped in the shortest distance using ABS-assisted panic brake applications, as shown in Figure 12 for the GVWR case (the braking performance of test vehicle "I" was not evaluated on this surface). When

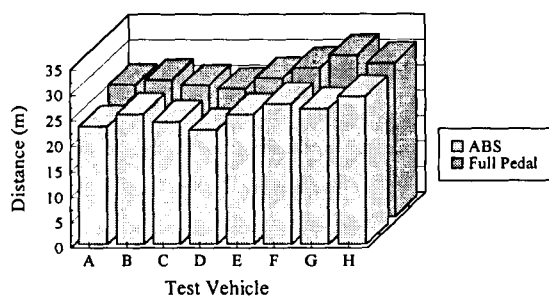


**Figure 11.** Straight line stopping distances observed on the wet asphalt/wet Jennite transition surface. Test vehicles were fully laden to their respective GVWRs.

lightly laden, the shortest stopping distance observed on ABS Test Pad #3 for vehicle "H" occurred when the driver utilized a panic brake application with the ABS disabled. In this case the ABS-assisted panic stop increased the vehicle's stopping distance slightly (2.0 percent) over the disabled ABS panic stop.

#### Split-mu Surface Braking

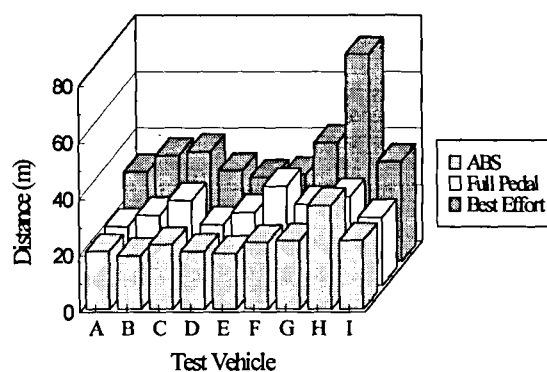
Under both loading conditions, seven of the nine test vehicles achieved the shortest wet asphalt/wet epoxy split-mu stopping distances when the driver used an ABS-assisted panic brake application (see Figure 13 for the fully laden results). When the ABS was disabled and a panic brake input applied, each test vehicle deviated from its stopping lane by yawing out of control (in fact, test vehicle "F" spun 180° for both loading conditions). With ABS, however, the driver



**Figure 12.** Straight line stopping distances observed on ABS Test Pad #3 (wet). Test vehicles were fully laden to their respective GVWRs. Vehicle "I" braking performance was not evaluated.

had no problem maintaining control of each vehicle while braking during the maneuver. These results provide a clear demonstration of how beneficial the assistance of ABS was for this test condition.

The shortest stopping distances for vehicle "H" and "I" were achieved with a panic brake application and disabled ABS. For vehicle "H", the disabled ABS panic stops provided lightly laden and fully laden stopping distances 29.3 percent and 16.5 percent shorter than the ABS-assisted stops, respectively. The same brake application and disabled ABS also resulted in the shortest stopping distances for vehicle "I", although with much less difference when lightly laden. The disabled ABS panic stops provided lightly laden and fully laden stopping distances 13.3 percent and 0.8 percent shorter than the ABS-assisted stops,



**Figure 13.** Straight line stopping distances observed on the wet asphalt/wet epoxy split-mu surface. Test vehicles were fully laden to their respective GVWRs. Note: the epoxy surface was reconditioned prior to the brake performance evaluation of vehicles "H" and "I".

respectively, for test vehicle "I". Both of these vehicles, however, deviated nearly 3 m (10 ft) from their 3.7 m (12 ft) wide stopping lane, under each loading condition, with the ABS disabled due to yaw induced by the lane's two frictional coefficients.

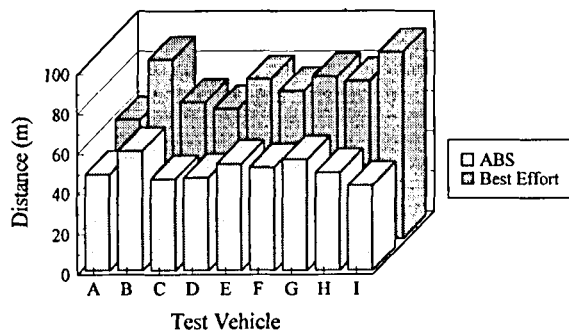
The large stopping distance differences between the ABS-assisted and best effort stopping distances for vehicle "H" were most likely due to the extremely low frictional coefficient of the resurfaced epoxy pad and the test driver's unfamiliarity with its characteristics. The surface made it much more difficult for the test driver to prevent wheel lock up through brake force modulation with this vehicle than with those driven prior to it. As the driver became more familiar with the surface, after vehicle "H" testing was complete, the

driver was able to better modulate pedal applications to optimize braking. This is indicated by the significant decrease in the ABS-assisted/non-ABS best effort stopping distance differential for vehicle “I” when compared with the results obtained from vehicle “H”.

### Braking in a Curve

Two tests involved braking in a curve of known radius: stops made on the wet Jennite 152.4 m (500 ft) radius curve and dry asphalt 91.4 meter (300 ft) radius curve. None of the test vehicles yawed out of control and, with one exception, stopping distances on the wet Jennite curve were found to be shortest with ABS-assisted panic applications at both loading conditions (Figure 14). The stopping distance achieved by test vehicle “A” using a best effort pedal application was 3.7 percent shorter than the comparable ABS-assisted distance on the wet Jennite curve when lightly laden. Note that test vehicle “I” was not evaluated on this curve when lightly laden.

Eight of the nine test vehicles were stopped in the shortest distances using ABS-assisted panic brake applications on the dry asphalt curve (Figure 15). This trend was not observed for test vehicle “I”, as its ABS-assisted stops were observed to be longer than the driver’s best efforts when lightly laden and at GVWR, 22.5 percent and 11.4 percent, respectively. Analysis of vehicle “I’s” braking performance indicated that when a panic brake input was applied while the vehicle was experiencing a high lateral acceleration, the ABS would release brake line pressure at all four wheels and hold it very low during the first few seconds of the braking maneuver. As the vehicle scrubbed off speed, line pressures were gradually allowed to build. It was not until late in the braking maneuver that brake line pressures were allowed to increase to a level great



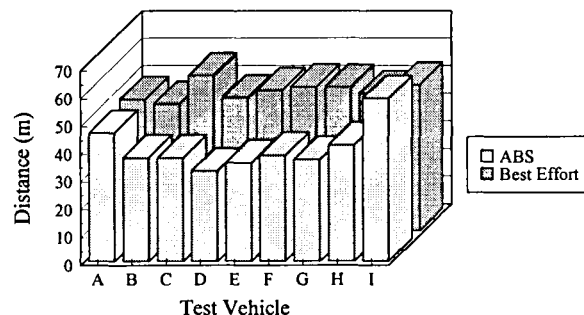
**Figure 14. Stopping distances observed on the 152.4 m (500 ft) wet Jennite curve. Test vehicles were fully laden to their respective GVWRs.**

enough to significantly affect the vehicle’s longitudinal deceleration. It should be noted that test vehicle “I” was the only vehicle whose ABS included the capability to monitor the vehicle’s lateral acceleration. Further investigation is necessary to determine whether this feature contributed to the apparently extended stopping distances.

### J-turn Stopping Maneuver

The J-turn maneuver was designed to observe ABS braking performance while a test vehicle was undergoing hard cornering. Each ABS prevented the test vehicles from yawing out of control, and allowed seven of the nine test vehicles to perform as expected. Vehicles “C” and “I” did exhibit noteworthy braking behavior (see Figure 16 for the fully laden vehicle stopping distances).

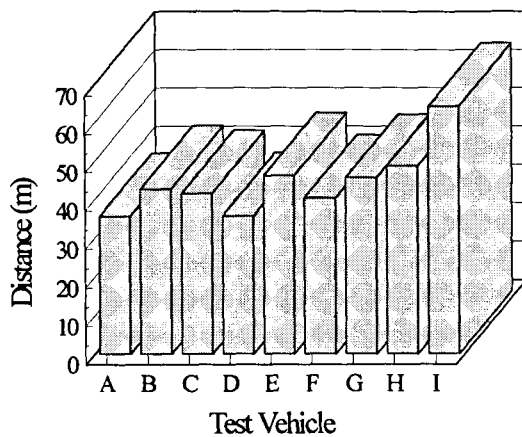
Test vehicle “C” deviated an average of 2.5 m (8.3 ft) from its intended stopping lane in each of the three ABS-assisted panic stops when lightly laden. This vehicle’s stopping distances were not noticeably extended, however, and the ABS was not considered to



**Figure 15. Stopping distances observed on the 91.4 m (300 ft) radius dry asphalt curve. Test vehicles were fully laden to their respective GVWRs.**

be responsible for this occurrence. For this case, it was believed that the lateral road holding capacity of the test vehicle was exceeded as it entered the J-turn, inducing understeer. The understeer condition subsided as the vehicle was slowed, and there was no excessive yaw present throughout the stop.

When fully laden, test vehicle “I’s” J-turn stopping distance increased 49.1 percent over the lightly laden distance. This increase was far greater than the average increase of the other vehicles (3.4 percent) and its cause is unknown. The test driver’s steering and brake inputs were nearly identical for both loading



**Figure 16. J-turn stopping distances observed on dry asphalt. Test vehicles were fully laden to their respective GVWRs.**

conditions, yet the vehicle's braking performance differed significantly.

### HUMAN FACTORS CONSIDERATIONS

Each test vehicle provided the driver with brake pedal and aural feedback while the ABS was cycling. The test driver would often experience vibration and oscillation of the pedal and easily hear the operation of the solenoid valves and ABS pump motor. The extent to which these signals were in evidence, however, varied from vehicle to vehicle. Even the vehicle whose ABS had virtually transparent pedal feedback presented the driver with very apparent aural cues. The point is that in each case, the vehicle "told" the driver the ABS was operating.

What makes this interesting from a human factors standpoint is that the antilock brake systems of some vehicles were found to transmit different cues under different driving conditions. If an ABS was activated on a very low coefficient surface such as epoxy, it would go into a deep cycle to keep wheel slip at an acceptable level. The corresponding pedal feedback, on some vehicles, was much more pronounced during deep cycling and could, potentially, startle an unfamiliar or unsuspecting driver. The result, depending on the severity of the condition necessitating the brake application, could be that the driver lifts their foot and releases the brake pedal. Even if the driver reapplies the brakes, this action will result in dramatically increased stopping distances.

The preliminary results of NHTSA's Light Vehicle ABS Research Program Task 5.2 indicate that braking practice may influence a driver's ability to avoid a collision in a crash imminent situation with ABS. When combined with the fact that ABS brake pedal feedback may vary with respect to road condition, braking practice may have important implications.

An ABS allows a driver to maintain directional control of their vehicle and enhances vehicular stability while braking. However, ABS requires the driver to maintain positive force on the brake pedal throughout the entire duration of the stop. To prevent the driver from being surprised by ABS behavior and its resulting pedal feedback, if any, drivers should be encouraged to practice ABS braking. Such braking practice, however, should consist of maneuvers compatible with the driver's level of skill.

### CONCLUSIONS

The results of this study indicate that for most stopping maneuvers, made on most test surfaces, ABS-assisted panic stops were shorter than those made with best effort or full pedal applications with the ABS disabled (see Table 4). Furthermore, the vehicular stability during these stops was almost always found to be superior with ABS. Although it was not specifically quantified in this study, the absence of excessive yaw while braking enhanced the ease at which the driver could maintain lane position, especially when compared to stops made with panic brake applications and the ABS disabled on split-mu and low coefficient surfaces.

The one systematic exception to this trend occurred on the loose gravel surface, where stopping distances with ABS were extended by an overall average of 27.2 percent over the disabled ABS full pedal application stops. The ABS-induced stopping distance increases were recorded for each vehicle at both loading conditions. Braking performance on this surface therefore comprises an area in which future efforts to improve ABS might be focused.

The fact that there exists a condition in which ABS actually proves to be universally detrimental proves compromises in ABS design exist. Most passenger vehicles spend much more time on smooth, paved roads than they do traveling over deformable surfaces such as gravel. Optimizing ABS behavior for such surfaces would likely involve increasing the amount of allowable longitudinal wheel slip. This could, however, dramatically reduce a vehicle's ability to turn during an ABS-assisted stop, thereby reducing one

of the fundamental attributes of ABS (enabling the driver to effectively brake and steer simultaneously).

This study also establishes that antilock brake systems include compromises of stopping distance versus vehicular stability. Most antilock brake systems maintain vehicular stability while braking by minimizing excessive yaw. In a curve, this stability may be created by sacrificing the shortest attainable stopping distance. With this said, most test vehicles (only one exception was observed) were stopped in shorter distances with ABS than with ABS disabled best effort attempts for maneuvers that involved braking and steering (or steering and braking). Under these conditions, ABS prevented wheel lockup and minimized yaw for each of the nine vehicles.

It was not the intent of this study to compare individual vehicles or antilock brake systems to one another. The test matrix was designed to examine the influence ABS has on a given vehicle's braking performance. Individual system comparison would have necessitated multiple samples of test vehicles identical in every way but ABS. Environmental conditions and test surface temperatures would also have been required to be held constant throughout the testing time line. Due to the time required for complete

instrumentation and the number of vehicles in the test fleet, such an evaluation would not have been possible.

Testing seems to indicate the increase in single driver run-off-road crashes is not due to the performance of ABS hardware. Preliminary investigation of NASS CDS crash reports (Task 3 of NHTSA's Light Vehicle ABS Research Program) shows that crashes occur most often on dry, paved roadways. Test track results, however, revealed that ABS performance was generally superior to disabled ABS performance over these surfaces. The varying brake pedal cues generated during an ABS-assisted stop (observed during testing), and the possible lack of driver familiarity with them, do provide some potentially valuable insight into the problem, however, as noted in section 7.0 of this report.

A definitive answer as to why the increase in ABS equipped, single-vehicle, run-off-road crashes exists remains elusive. NHTSA's Light Vehicle ABS Research Program will continue its exploration of all plausible reasons as to why the crash data studies do not show that ABS is improving automobile safety. Tasks 1 through 5 are currently underway, and the results will be forthcoming.

**Table 4.**  
**ABS Performance Summary**

Surface	ABS Stopping Distance Benefit (or Disadvantage) Over the Shortest non-ABS Stop (%)	
	Lightly Laden	Fully Laden
Dry Concrete Straight Line	9.8	12.7
Wet Polished Concrete Straight Line	16.7	23.1
Wet Asphalt Straight Line	11.4	17.2
Wet Jennite Straight Line	17.6*	26.6
Grass Straight Line	(7.1)*	6.9
Loose Gravel Straight Line	(30.0)*	(24.6)
ABS Test Pad #0	7.6	11.6
ABS Test Pad #1	6.2	10.3
ABS Test Pad #2	6.1	10.9
ABS Test Pad #3	4.6*	7.9*
Wet Asphalt/Wet Epoxy Split-mu	11.3	11.4
Dry Asphalt Curve	11.9	19.5
Wet Jennite Curve	18.9*	32.4

\*Percentage calculated using eight test vehicles.

## ACKNOWLEDGMENTS

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# HEADLAMP-BASED VISION SYSTEM AND THE VISION TASK

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## ABSTRACT

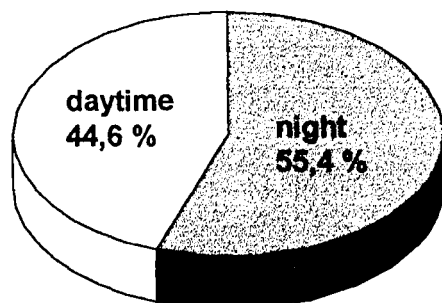
Today the driver's eyes collect all visual information on traffic flow and accident prevention. The intricate physiology of the human eye and the visual cortex is fit to discern vision noise from visual information sufficiently to guide a vehicle through traffic - in almost all cases.

The study of the performance of the vision system under disfavoured conditions exposes the limits. It provides immediate input to vision assistance. For example, it clarifies design criteria for more comfortable, hence safer, vehicle lighting systems. It assists the introduction of first, primitive vision functions in headlamps.

The paper details the study of visual performance, defines the resolution conditions for existing active safety devices and shows first examples of vision system applications in automotive headlamps.

## INTRODUCTION

In recent years, the number of sensors in motor vehicles has increased rapidly. The most important examples are pressure, acceleration and temperature sensors. The information these sensors supply is, however, almost exclusively concerned with the condition of the vehicle itself, but not with the surrounding environment, let alone with the traffic situation. This task is still entirely that of the driver. The only exceptions to date are sensors for outdoor temperature to warn drivers of potentially icy road conditions, as well as recently developed rain sensors to control the windscreen wipers for him. Sensors for ambient brightness are soon to come, which will serve the purpose of turning on the running lights when darkness falls.



**Figure 1.** Proportion of fatalities for day and night in Japan 1993.

84 % of the ambient information drivers have to sense and process in order to drive a vehicle safely through traffic is visual in nature [1], i. e. is input through the eyes. The human eye, and above all the subsequent information processing in the brain, is well-adapted to this task, although the system is sometimes ill-equipped to handle conditions of poor visibility, as seen in accident statistics. In Germany, for instance, about half of the accidents (49.6 %) in 1993 occurred at night [2]; in Australia, the percentage of night accidents was 43.8 % in 1995 [3] and in Japan 55.4 % [4] - see figure 1. To understand the significance of these figures, it must be remembered that only about 20 - 25 % of total driving time is at night. The comparison in figure 2 demonstrates that the cause of this disparity is to be found in the lack of information due to poor visibility. In addition to the examples of visibility hindrances listed there, darkness and rain, fog and snowfall also play important roles.



**Figure 2.** Comparison of vision conditions in daylight and at night.



The above examples make it clear that, at least under certain conditions, the driver of a motor vehicle can use some assistance and support to master the task of gathering sufficient information about ambient road and traffic conditions.

## **POTENTIALS FOR OBTAINING INFORMATION FROM THE AREA SURROUNDING THE VEHICLE**

One idea would be to transmit such information to the vehicle in automatically evaluable form. Since such a method requires a standardized infrastructure external to the vehicle, it will not be feasible within the near future.

The only remaining possibility is to use independent systems in the vehicle to obtain the necessary information. Various sensor systems offer potential solutions. Radar devices are surely the most familiar. Radar systems are designed to provide information on distances. The scanning systems used to obtain a flat image are expensive and complex. On the other hand, radar devices are not dependent on optical visibility.

Lidar (light detection and ranging) devices function similarly to radar, the difference being that they function on the basis of light instead of high frequency and hyperfrequency electromagnetic waves. This means they are dependent on optical visibility, although the equipment is usually not as expensive as radar devices.

Video methods are of course dependent on optical visibility, too. The big advantages of such systems is that the way they obtain information is very similar to the way human vision works. On the other hand, exact distance information is much more difficult to obtain with such devices.

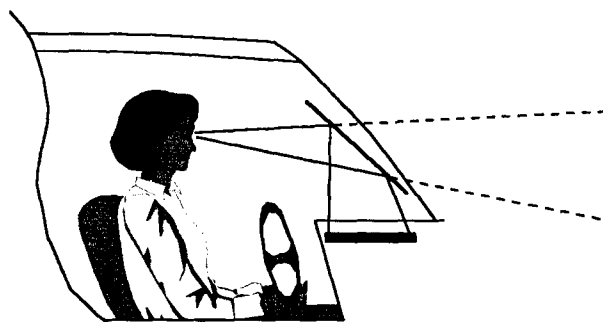
## **UTILIZATION OF INFORMATION FROM THE AREA SURROUNDING THE VEHICLE**

Utilizing information obtained from the area surrounding a vehicle represents a new technical field, so that it is important to begin by considering carefully what exactly should - and can - be done with such information. Such systems generally entail a problem inherent in the practically infinite number of potential constellations and input states. It is therefore impossible to check with 100 % certainty whether the system is reacting properly to all potential changes in the input parameters. Since the consequences of functional failures are considerable in terms of product liability laws, completely automated use of such functions, particularly in safety-relevant applications, will not be available for some time. The approach being taken at present is to design such systems as driver assistance systems, i. e. so that the driver can decide and react contrary to system recommendations at will. Full responsibility thus remains with the driver.

One example of such a driver assistance system is ACC (Adaptive Cruise Control) [5], series installation of which is

expected for 1999. In the initial version, it will be used with a radar sensor. The question has been raised as to whether drivers might be tempted to drive blindly through fog, trusting to the better "vision" of the radar system. This would be a case in which the driver relies entirely on the system, which is not in keeping with its design concept as a driver assistance system. This fact admittedly represents a risk factor.

Another approach draws the driver's attention to specific potential danger sources. During daylight hours, a head-up display could be used, correct control of which would have to take the driver's head position into account to ensure that the driver really sees the superimposed symbols in relation to the potentially dangerous object - see figure 3

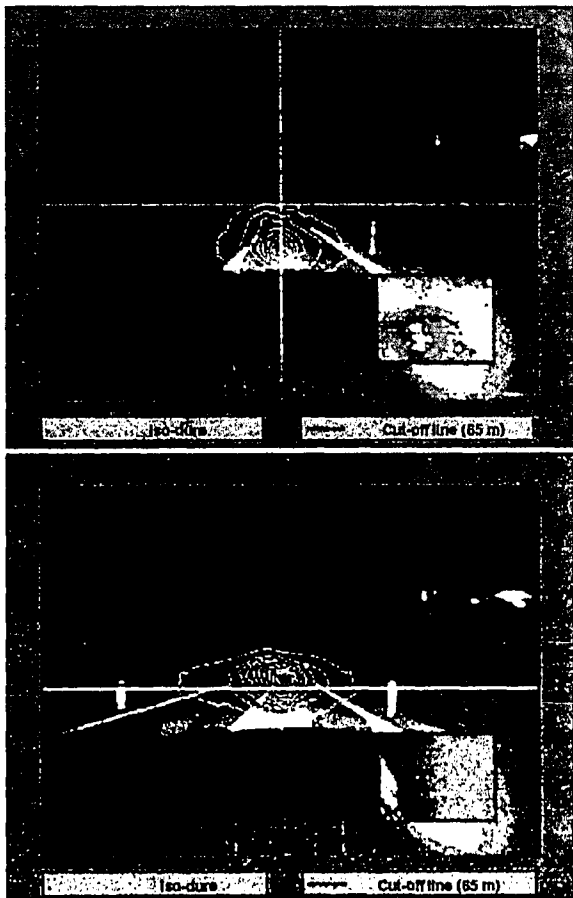


**Figure 3. Use of a head-up display for warning of potential dangers on the road.**

At night, a different method can be used: The attention of the driver can be drawn to specific points by means of light. Every driver is familiar with the effect of overly bright interior lighting distracting one's attention from what is going on outside the car at night. This effect is added to the reduction in object visibility resulting from diminished contrast. The headlamp light is predestined to influence the attention of the driver within the range that is particularly important for the operation of a motor vehicle.

## INFLUENCING VISUAL ATTENTION OF DRIVERS BY MEANS OF HEADLAMP LIGHT DISTRIBUTION

To achieve an active influencing of visual attention using headlamp light, it was first necessary to determine the principles on which the process is based. The corresponding studies were done by the "Auto, Sicht, Sicherheit" Research Group (ASS) in Cologne and Daimler Benz Forschung Fahrzeug, Abteilung Mensch und Fahrzeug in Berlin [6]. Figure 4 shows the influence of light distribution on the distribution of visual attention. Using headlamps with an emphasized close-range illumination area, as in the H4 system used here, a shift of vision towards the vehicle can be seen. The width of the 90 % area is also restricted on account of the "narrow" light distribution. Exactly the opposite can be seen in the case of the Xenon headlamp with its ellipsoid system and wide field of illumination at the cut-off line, whereby the 90 % area is substantially widened. The driver thus "scans" the more distant areas more intensely.



**Figure 4. Dependency of the visual attention on headlamp illumination distribution for H4 and xenon headlamps**

One can conclude from these results that the greatest light intensity will be applied where potential dangers could arise, and at a distance correlated with current driving speed. The future may bring the technical feasibility, and legal allowance, of light distribution that is freely adaptable to current road and traffic conditions, at which point these studies will require further refinement. At present, such unrestricted lighting practices are not yet in sight. Current considerations are therefore restricted to light distributions which, although fixed in themselves, are mobile in relation to the vehicle axes.

## CONTROL OF HEADLAMP LIGHT DISTRIBUTION

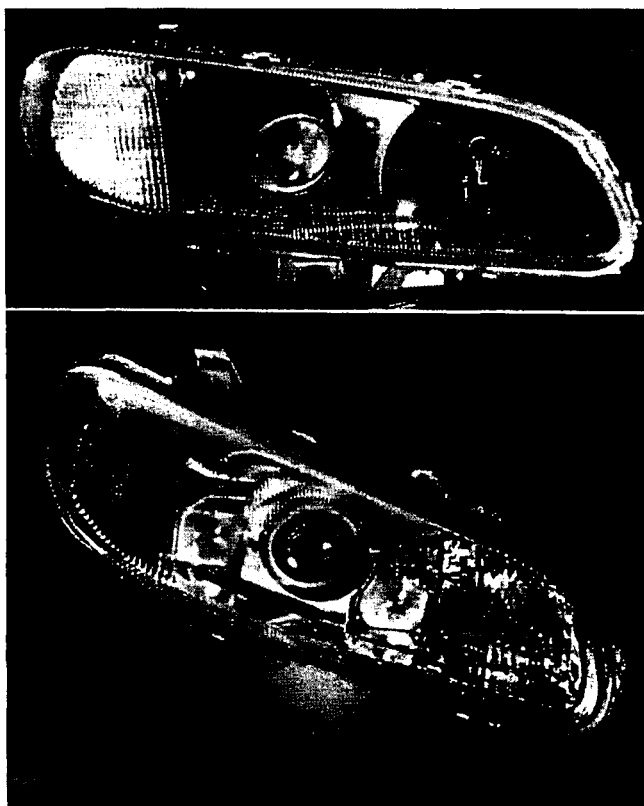
Control in relation to the vertical vehicle axis is a component of the dynamic cornering lighting [7] planned for AFS (Advanced Frontlighting System). Series production and use of such systems can be expected beginning in about the year 2003, since the regulations will have to be adapted to accommodate them. The current approach to control of dynamic cornering headlamps presupposes that the necessary information can be obtained with the aid of yaw and steering angle sensors. Testing of the corresponding prototype vehicles reveals the imperfection of the method, since these sensors can only provide a curve datum for the current vehicle position, whereas the headlamps illuminate the route in front of this. What is actually needed is data on the course of the road in front of the vehicle. Such information can be provided with the sensor systems mentioned earlier [8].

Control and steering of movements about the longitudinal axis is not important in automobiles, although it could make a significant contribution to motorcycle safety. A prototype developed by Hella demonstrated its performance capability in the Daimler Benz research vehicle F 300 Life-Jet [9], which was introduced to the public at the IAA 97.

Control about the transverse axis of the vehicle is already realized by automatic headlamp levellers today. Dynamic headlamp levellers - used particularly in combination with Xenon headlamps - compensate not only various load states, but pitching movement as well, for instance during acceleration and braking. A more precise analysis of the reactions of these systems reveals that the axle sensors currently used to obtain control information are only capable of determining the position of the vehicle in relation to the road in the area immediately adjacent to the vehicle, so that the headlamp ranges set near hilltops and dips are either too great or too small. Just as with the vertical axis, only sensors that see what is coming can provide perfect results.

## APPLICATION OF VISION SYSTEMS FOR HEADLAMP CONTROL

The problem of implementation of a sensor that sees what is coming, i. e. a vision system, to control headlamps would suggest use of a video camera in the headlamp itself. Firstly, this would result in a compact device; secondly, the optical axes of at least one headlamp and the camera would be nearly contiguous. Locating the vision system behind the windscreen, as has been repeatedly proposed, would have neither of these advantages. On the other hand, the requirements placed on the system with regard to temperature resistance and other environmental influences would be much tougher.

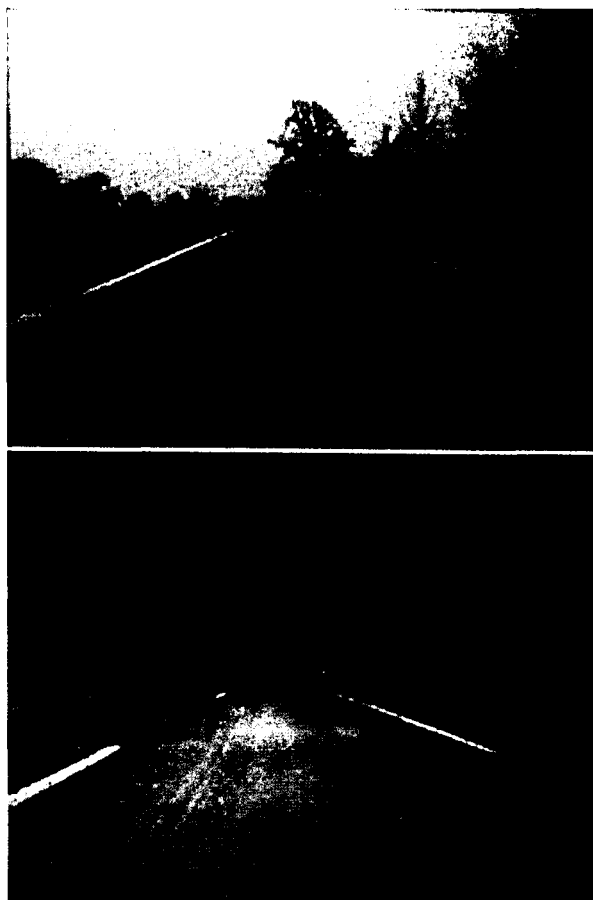


**Figure 5.** Hella's test bed for headlamp-based vision systems and a headlamp with Lidar sensor.

Figure 5 shows the system Hella constructed to test camera systems in the headlamp. Modern headlamp designs without optical lens patterns are favourable to such applications, although no experiential data is available on optical influences that were of little significance to date, influences that will have to be taken into account when installing the camera. Figure 6 shows images photographed by this camera on the road.

## FUTURE DEVELOPMENTS

The advantage of this headlamp-based vision system is that one and the same sensor can be used to obtain much more data, which can in turn be used for further tasks. Examples of this include drowsy / inattentive driver warning systems, lane deviation warning systems, vehicle distance warning systems and position-regulated speed control systems (ACC) [10].



**Figure 6.** Examples of video images taken with Hella's headlamp-based vision system.

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## BEHAVIOURAL ADAPTATION TO FATIGUE WARNING SYSTEMS

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### ABSTRACT

Driver impairment due to fatigue induced drowsiness is a significant cause of vehicle collisions. One countermeasure that is currently being implemented is Fatigue Warning Systems (FWS) to alert drivers that are drowsy. Behavioural adaptation of drivers to a FWS was evaluated in a closed track study. Thirty-two drivers completed two lengthy overnight drives, separated by one week, with half the drivers completing the second drive with an active FWS. During the drives, drivers voluntarily took breaks for as long as they liked. Behavioural results demonstrate that the FWS had no impact on objective and subjective driver fatigue, on driving time, on the number of breaks or on break duration. Results also demonstrate that 30 minute breaks are an ineffective drowsiness countermeasure. These findings suggest that a FWS as currently conceived may not contribute to reduce fatigue induced collisions.

### INTRODUCTION

One important cause of single and multiple vehicle collisions is driver impairment due to drowsiness (Wierwille et al., 1994). Fatigue related impairment has been estimated to be a contributing factor in 30% to 40% of heavy truck collisions (AAA Foundation for Traffic Safety, 1985; National Transportation Safety Board, 1990) and causes approximately 6% of single vehicle roadway departure crashes (Knippling, personal communication, 1996). Drowsiness and inattention may contribute to approximately one million collisions annually in the U.S. which represent one-sixth of reported collisions (National Sleep Foundation, 1996). The incidence of driver drowsiness is underestimated in police reported crashes due to the difficulty in determining unequivocally that drowsiness was the primary cause of a specific collision. It has also been reported that 31% of drivers who experienced drowsiness were initially unaware of its onset (Skipper & Wierwille, 1986). The United States Department of Transportation and Federal Highway Administration have identified driver fatigue as a priority road safety issue.

Studies investigating the effects of driver fatigue on driving have typically implemented vehicle control and psychophysiological measures as indices of driver drowsiness. Generally, studies have found that time of day has a larger

impact on driver fatigue than time on task (Brown, 1994; Gillberg, Kecklund, & Åkerstedt, 1996; Mitler, Miller, Lipsitz, Walsh & Wylie, 1997; Wylie, Shultz, Miller, Mitler, & Mackie, 1996).

Fatigue warning systems (FWS) have been proposed as specific countermeasures to reduce collisions associated with driver fatigue. These devices employ a variety of techniques for detecting driver drowsiness while operating a vehicle and signal a driver when critical drowsiness levels are reached. However, the detection of driver fatigue using valid, unobtrusive, and objective measures remains a significant challenge. Detection techniques use lane departure, steering wheel activity and ocular and facial characteristics.

Brown (1994) views fatigue as the subjective experience of tiredness combined with a disinclination to continue performing a task. He argued that countermeasures against fatigue will be successful to the extent that they correlate with the driver's subjective experiences of fatigue. This contention stands in sharp contrast to current approaches to fatigue warning systems (FWS) that attempt to develop objective measures of fatigue to warn the driver at the earliest possible moment of fatigue. Systems presently under development use vehicle control measures or video analysis of drivers' facial and ocular features. Several types of measures have been investigated that fall into three broad categories: physiological measures, vehicle control measures, and subjective driver evaluation measures. This study investigated behavioural responses to FWS. In particular, the focus was behavioural adaptation and the effectiveness of breaks in reducing drowsy driving.

### Behavioural Adaptation

Assuming that the technology for detecting drowsiness can be perfected, there remains a concern that drivers may use such systems as an 'alarm clock' to keep them awake and allow them to continue driving even when extremely drowsy. There is anecdotal evidence that heavy truck drivers use unpaved shoulders in such a way (rumble strips also have a similar effect). Such unintended use of FWS is an instance of behavioural adaptation.

The Organisation for Economic Cooperation and Development (OECD, 1990) defined behavioural adaptation

as follows: "Behavioural adaptations are those behaviours which may occur following the introduction of changes to the road-vehicle-user system and which were not intended by the initiators of the change (OECD, 1990; p.23)."

The OECD report concluded that road users adapt their behaviour to changes made to the road transport system (road, vehicle and road user) to increase their mobility and thereby reduce the safety impact of the change. This phenomenon may be a widespread response to improvements in safety (Janssen, 1994; Wilde, 1994).

Research performed by the Ergonomics Division of Transport Canada has demonstrated that behavioural adaptation may diminish the benefits of Antilock Brake Systems (ABS) present in vehicles following a drivers' exposure to ABS (Grant & Smiley, 1993). A recent study by Sagberg, Fosser and Saetermo (1997) reported that taxi drivers with ABS showed significantly reduced headways. However, airbags were not found to be associated with changes in driving behaviour. Certain personality traits (e.g., sensation seeking, extroversion-introversion) may exacerbate behavioural adaptation and thereby further reduce the impact on safety for such individuals. Given that behavioural adaptation has been shown to influence the effectiveness of countermeasures, the question arises, to what extent do such effects extend to FWS. To date, no study has reported on the impact of behavioural adaptation to FWS.

The purpose of the present study was to assess the extent to which behavioural adaptation can occur in response to the FWS. It is possible that driving performance will improve in the presence of a FWS if the system decreases driver drowsiness. Behavioural adaptation was investigated by recording changes in driver performance (e.g., lane deviation, driving speed, steering wheel changes) and behaviour (e.g., number of breaks, break duration, subjective fatigue level, eye-closure frequency, objective fatigue level).

The primary behaviours of interest are the occurrence of breaks and measures of fatigue. Subjective fatigue, being a sensitive measure demonstrated to correlate with EEG and driving performance measures will also be evaluated. One group of drivers were subjected to the FWS while a second group drove without the system. It should be noted that our goal is to investigate FWS in general and not to assess the effectiveness of particular implementations of such systems. Given the limitations of current technologies to reliably detect drowsiness we have decided to use the most sensitive fatigue detector available: a human observer. The observer triggered the FWS when certain specified fatigue criteria were met.

**Drowsiness Measures** - Numerous measures have been used in an attempt to detect sleep onset. These include increased slow rolling eye-movements, decreases in behavioural response to stimulation, delayed response time to a vigilance task and shallow respiration (Ogilvie et al., 1985; Ogilvie et al, 1989). Ogilvie and colleagues also report that the change from wakefulness to Stage 1 sleep is associated

with a significant increase in Stanford Sleepiness Scale (SSS) values. The SSS was developed by Hoddes et al. (1973) on sleep deprived individuals. The scale is a simple 7-point Likert rating scale designed to assess sleepiness. The physiological concomitants of sleepiness, as measured by EEG, were found to correlate with SSS scores. It may therefore be possible to use behavioural measures such as slow rolling eye-movements or fatigue scales instead of more complex EEG measures.

O'Hanlon and Kelley (1977) were able to discriminate between good and poor drivers, during a long duration nighttime driving task, using measures such as speed variability near the end of the drive, rate of large steering wheel movements (greater than 10 degrees) and lane deviation. The differences were amplified during later trip segments. Drivers' self ratings of fatigue and alertness did not reflect differences in performance, though good drivers rated their alertness higher and their fatigue lower than poor drivers. However, vehicle control measures were not as sensitive to group differences as were heart rate and EEG measures.

Riemersma et al. (1977) measured reaction time to a vigilance task, vehicle control measures and heart rate during an eight hour overnight drive. The results of the subsidiary reaction time task showed decrements in performance during the drive. Lane position variability and speed variability increased with driving time. Heart rate and heart rate variability decreased primarily in the first part of the drive. Subsidiary reaction time tasks and vehicle control measures were both sensitive to the effects of fatigue. However, the authors interpreted the decreases in heart rate and heart rate variability as being associated with habituating to driving rather than indexing increases in fatigue.

Khardi and Vallet (1994) developed a ratio derived from EEG theta activity relative to alpha activity and found it to reflect a decrease in driver vigilance. They then compared changes in the ratio to changes in steering wheel activity associated with decreased vigilance as determined with EEG criteria. The authors found that small magnitude steering wheel movements decreased in frequency while large magnitude steering wheel movement increased in frequency with drive time. The threshold derived for small magnitude steering wheel movements was between 0.5 and 2 degrees while for large magnitude steering wheel movements it was 7.2 degrees. These steering thresholds derived from EEG criteria may be useful in detecting decreased driver vigilance.

Åkerstedt and Gillberg (1990) found that subjective sleepiness was associated with increased energy levels in the alpha and theta bands of the EEG signal. The EEG changes did not appear until subjective sleepiness was considerable. Slow eye-movements were also correlated with subjective sleepiness.

Siegmund, King and colleagues (King, Siegmund & Montgomery 1994; Siegmund, King, & Mumford, 1995; Siegmund, King, & Mumford, 1996) have investigated three

types of measures to determine the best measure to evaluate driver fatigue in 17 heavy truck drivers on a closed track. The physiological measures investigated were EEG and heart rate. The vehicle control measures recorded were vehicle speed and distance, steering wheel angle and angular velocity, accelerator pedal angle, accelerator pedal angular velocity and pace-vehicle following distance. The behavioural measure of drowsiness was a rating of video images using facial and ocular features, as developed by Ellsworth and Wierwille (1994). The rating scale was a five point Likert scale: Not Drowsy, Slightly Drowsy, Moderately Drowsy, Very Drowsy, and Extremely Drowsy. The correlations for interrater and test-retest reliability were both greater than 0.8.

Drivers completed a driving task under normal sleep conditions and under sleep deprivation. The authors then correlated all measures to determine which would best index fatigue related changes in driver behaviour. A positive correlation was uncovered between EEG and the subjective evaluation of drowsiness for 10 of 17 drivers tested. EEG and steering behaviour were significantly correlated for 8 of the 17 drivers. Correlation between lane keeping and EEG was stronger than correlations involving steering activity and EEG.

Heart rate correlated well, for five of 11 drivers with reliable data, with the vehicle control measures. The subjective measure of drowsiness correlated most strongly with vehicle based measures. Steering angle standard deviation and large steering reversals correlated most strongly with the subjective measure of fatigue. Lane control measures, particularly centerline deviation, also correlated quite well with the subjective measure.

The authors confirmed that since the lateral position maintenance of the vehicle inside the lane is the highest-order continuous task performed by a driver, this measure was most sensitive to driver fatigue. This is based on the view that the subjective evaluation of drowsiness was the standard measure of fatigue against which other measures would be evaluated (Siegmund et al, 1995).

Skipper, Wierwille and Hardee (1984) studied sleep deprived drivers performing a 1.5 hour driving task. They report that performance measures such as lane deviation and steering velocity were highly correlated with eyelid closures.

Skipper and Wierwille (1986) investigated several dependent measures to discriminate between drowsy and alert drivers. Measures included percent eyelid closure, low velocity steering reversals, and standard deviation of lane position. Two driving control measures were highly weighted within the discriminant function: standard deviation of low steering velocity and standard deviation of lane position. False alarms for alert drivers was approximately 37% while for drowsy drivers it was approximately 15%. In a subsequent study, Wierwille et al. (1994) found that a linear combination of an eye closure measure, two EEG measures and two heart rate measures can provide a good predictor of cognitive task performance in sleep deprived individuals.

In summary, several studies have demonstrated significant correlations between changes in vehicle control measures and physiological (EEG) and subjective indices of drowsiness. This has led to interest in developing vehicle control-based measures to assess driver drowsiness to replace more difficult to measure and interpret physiological indices of driver drowsiness. Given that no single measure emerged from the literature as an unequivocal index of drowsiness in drivers, the present study used criteria based on physiologically relevant eye-closure duration and vehicle lateral control to trigger the FWS.

**Impact of Breaks On Fatigue** - Drivers employ different coping strategies in dealing with drowsiness while driving. Drivers may stop, stretch or ingest coffee when they are drowsy. However, little research has been performed on the effects of break frequency and duration on driving performance. Drory (1985) studied truck operators performing a seven-hour simulated overnight driving task divided into 21 blocks of 15 minutes. In addition to driving, some drivers were required to complete a vigilance task or a voice communication task.

The design provided two rest conditions: normal rest (6 minutes following each block) representing the time it took to unload and extra rest (30 additional minutes with drivers showering and ingesting coffee following three hours of task time). Driving performance measures included reaction time to simulated brake lights, number of brake responses, and steering wheel reversals. Voice communication was associated with shorter brake reaction time and fewer steering reversals relative to driving alone. The voice task was also associated with the highest reported subjective fatigue level. The extra rest reduced subjective fatigue level but failed to significantly impact the driving performance measures. Consequently, longer breaks may not provide any additional benefits in decreasing objective indices of drowsiness.

Lisper and Eriksson (1980) reported on the effects on subsidiary reaction time performance of a 15 minute versus a 60 minute break with or without food halfway through an eight hour driving task. They found that breaks without food did not impede deterioration in performance regardless of break duration. However, eating was found to reduce deterioration in performance.

Lisper, Laurell, and van Loon (1986) investigated the time for drivers to fall asleep while driving on a closed track and the effect of breaks. On average, drivers' first bout of falling asleep occurred in the last third of a 12 hour drive. The time between the first time drivers fell asleep behind the wheel and two subsequent instances of sleep epochs averaged 24 minutes with a range covering 5 to 60 minutes. The time to falling asleep behind the wheel following a brisk walk averaged 23 minutes. Consequently, breaks did not seem to prevent the onset of sleep while driving but acted to delay sleep onset.

Recently, Nilsson, Nelson, and Carlson (1996) showed that multiple rests delayed fatigue onset to a greater extent relative to long breaks. Gillberg, Kecklund and Åkerstedt (1996) required professional drivers to complete a simulated driving task during day and night. The day drive consisted of three 30-minute task blocks. The night drive consisted of the middle driving block being replaced with a break or a nap. Mean speed was found to be higher during the day drive. Lane position varied significantly less during the day drive. Subjective and objective drowsiness was higher during night driving and increased with task time. Neither the break nor the nap was found to have any impact on drowsiness or driving performance in this limited study.

In summary, most studies have reported little benefit of breaks in reducing drowsiness levels in drivers. However, in the natural driving situation breaks are voluntary and last for as long as the driver feels is necessary. This latter type of break may be more effective in reducing driver fatigue compared to a fixed break regimen. No one to our knowledge has studied the effectiveness of self-initiated breaks.

## METHOD

### Drivers

Thirty two drivers (seven females and 25 males) between the ages of 17 and 38 years (median age 22 years) participated in the study. All drivers were recruited from two universities in proximity to the testing facilities and were paid a fixed sum of \$150 for their time at the end of the second test session. No driver had previous experience participating in a driving study and all had a valid driver's license. Each driver participated in two sessions each on separate nights.

### Experimental Design

The design was a 2X2 mixed design. Drivers were randomly assigned to one of two groups: the Fatigue Warning System (FWS) group and the Control group. The within-subjects factor was session with two levels (Baseline, Test). Generally, when no warning system was present we expected no differences in behaviour between the two groups of drivers. Also, all drivers completed the Zuckerman Sensation Seeking Scale Form V (Zuckerman, 1979). The scores on the scale vary from 0 to 40, with a high score indicating increased propensity towards sensation seeking. A median split was performed to classify drivers as high and low sensation seekers which comprised an additional nested two level factor: Trait (high and low). The median score for sensation seeking was 20 for all drivers tested. Student's t-test indicated a significant difference between high and low sensation seekers on the Zuckerman scale [ $t(31)=5.77$ ,  $p<0.001$ ; Means:

Low=17.81, High=25.5]. See Jonah, Thiessen, and Vincent (1997) for results contrasting low and high sensation seekers.

**Apparatus** - A four door 1992 Cutlass Ciera was instrumented to collect and record the following parameters:

- video of driver's ocular and facial features
- vehicle speed and distance
- steering wheel angle
- vehicle lane position

A Panasonic microcamera, installed underneath the rear-view mirror, recorded changes in the driver's ocular and facial features. Two matrices of infrared LEDs were used to increase the brightness of the video images during night driving. No light was perceivable by the vehicle occupants. A speed pulse transducer installed on the rear wheel recorded vehicle speed and distance. A potentiometer encoder was mounted on the steering column to record steering wheel angular position. To record lane deviation, a Human Factors Research corporation lane tracker was mounted on the trunk of the vehicle pointed at the lane line. All signals were sampled at a rate of 10 Hz and were recorded using a laptop computer.

The FWS was operated by a 'fatigue observer' seated in the backseat of the vehicle. The fatigue observer was responsible for detecting driver drowsiness and activating a warning tone. The observer used two sources of information to determine driver drowsiness; lane position and eyelid closure based on a technique developed by Wierwille (see Wierwille & Ellsworth, 1994) and applied in real-time using the video image of the driver's facial features. Two independent criteria were used to activate the signal. A tone was presented to the driver whenever the eyelids closed for longer than two seconds. The second criteria incorporated lane tracking standard deviation. The computer was programmed to signal the fatigue observer whenever lane position standard deviation exceeded 0.45m (1.5 feet). The fatigue observer activated the FWS signal when a lane deviation signal was followed within the next minute by the driver's eyelids closing for more than one second.

### Procedure

Participants were requested to complete two night driving sessions of approximately five hours, each one week apart, on a closed test track. The test track used consisted of a two-lane oval covering a distance of 6.9 km. Prior to the first (Baseline) session drivers were sent: i) a copy of the consent form to review, ii) a list of caffeinated items to avoid the day of the drive, iii) a sleep log to be completed for each of two days prior to testing.

Drivers were instructed to stay awake on the day of the session from 0700 h until the start of the drive at approximately 2200 h. and to abstain from alcohol and



caffeinated items on the day of each drive. Drivers were escorted to the testing facilities by 2115 h. Upon arrival they were asked to complete the consent form, the sensation seeking scale, the Stanford Sleepiness scale, a fatigue-alertness adjective checklist and a breathalyzer test. Any driver with a blood alcohol concentration (BAC) greater than zero would have been discarded from further testing. No driver was discarded due to a non-zero BAC.

Prior to the start of the drive, drivers were informed that two passengers would be in the vehicle throughout the drive. The first was a safety observer in the passenger seat. This observer would activate a secondary brake coupled to an engine shut/off system if an unsafe situation arose. Drivers were informed that the safety observer could ask to be relieved when tired. The second was a fatigue observer, seated in the rear who started the equipment, checked data acquisition throughout the drive and activated the fatigue signal. Drivers were not informed that the observer activated the FWS.

At approximately 2200 h, the driver was instructed to enter the vehicle and adjust the seat/mirrors and prepare to complete two practice laps. Approximately 15 minutes were required to complete two practice laps. Drivers wore headphones to receive the warning signals. Drivers were informed that they could not hold a conversation with the passengers, that they could not use the radio or air conditioning. They were permitted to open the driver's side window.

Drivers were instructed on how to enter their subjective level of fatigue using a microswitch interfaced to a LED display. The digital display allowed values to be entered ranging from 0 to 99. The display automatically reset to zero three seconds after a value was entered. The value 1 represented the state that 'I can continue driving without any problems' and 99 represented 'I definitely need a break'. Drivers were instructed to enter a value every two laps and just before stopping for a break.

For the Test laps, the drivers were instructed to drive 350 km at a speed of 70 km/h. However, drivers were told that if they felt they could not complete the session they could withdraw at any time. Cones were placed at 200 m intervals along the test track just on the other side of the median lane line. Drivers were informed that the cones along the track were to be avoided and if any cone was touched a 15 minute break (i.e., penalty) would be imposed.

Immediately after the practice period, drivers were instructed to commence the drive. Depending on break frequency and duration, the experimental session took between five and six hours to complete. The duration of each session varied for each individual driver.

Drivers were informed that during the drive they were free to take as many pauses as they wished for as long as they wished but they were not permitted to nap. When drivers requested a pause, they were asked to enter their subjective

fatigue level and to estimate their sleepiness with the Stanford scale. During the break, drivers were provided with juice, water, and a place to rest. Prior to the restart of the drive, drivers were instructed to enter their subjective fatigue level and to complete the Stanford scale. Drivers who terminated the drive because they felt incapable of safely continuing were asked to complete the Stanford scale within the vehicle and then debriefed.

During the practice laps prior to the start of the Test session, drivers in the FWS group were provided with the opportunity to experience the effects of a FWS. They were informed that the instrumented vehicle contained specialized equipment to detect and signal fatigue to the driver. Drivers were informed that the system assessed numerous aspects of driving performance and behaviour to detect fatigue. Drivers were instructed that the system would alert them using a tone presented through the headphones. They then received direct experience with the system. Drivers were asked to complete two practice laps around the track and at specified points during the laps were presented with the auditory signal. The control group of subjects during the test received the equivalent amount of driving practice but without the FWS. In other words, the baseline protocol was repeated.

## RESULTS

### Analysis

Two types of response measures were recorded during the test sessions: behavioural and primary task performance. These measures were recorded to determine the effect of driver fatigue on driving with and without a FWS and to assess the impact of behavioural adaptation to the FWS. Behavioural measures included: number of breaks, duration of breaks, the number of warning tones received by FWS drivers, reported levels of subjective fatigue, and objective fatigue levels using a modified PERCLOS method and eye-closure frequency. The PERCLOS method consisted of off-line video analysis to determine the extent of eye-closure for given periods of time. Primary task measures included: lane position, the number of cone collisions, driving speed and steering wheel changes. The present report documents only the results derived from behavioural data.

**Summary Information** - Tables 1 and 2 present summary data for each driver during each test session for the Control group and the FWS group respectively. Statistical tests were performed to determine if the groups differed in behaviour between sessions but within groups, and within sessions but between groups. Mixed design analysis of variance (ANOVA) tests were performed separately on the measures presented in tables 1 and 2. The ANOVAs included Group (Control, FWS) as a between-subjects factor and Session (Baseline, Test) as a within-subjects factor.

The ANOVAs for distance completed, session duration, and break duration did not uncover any significant effect of Group, Session or their interaction. The values as a function of each driver are presented in tables 1 and 2.

An ANOVA was performed on sleep duration. The ANOVA for reported sleep duration two days before a test session did uncover a significant main effect of Session [ $F(1,30)=6.32$ ,  $p<0.02$ ]. Drivers reported on average longer sleep duration prior to the Baseline session (8.28 hours) relative to the Test session (7.33 hours). No other effect was significant. A similar test performed on reported sleep duration one day prior to testing, uncovered a marginally significant Group by Session interaction [ $F(1,30)=3.83$ ,  $p<0.06$ ]. Drivers in the Control group reported significantly less sleep one day prior to the Baseline session (6.26 hours) relative to the Test session (7.09 hours). No main effects were significant. Parallel effects were not uncovered in reported quality of sleep two days and one day prior to testing. However, moderate positive Pearson correlations were found between quantity and quality of sleep within both groups (Control 2 days,  $r=0.52$ ; 1 day,  $r=0.30$ ; FWS 2 days,  $r=0.40$ ; 1 day  $r=0.60$ ). In summary, the control and FWS drivers do not differ to a large degree on the parameters presented in tables 1 and 2.

**Impact of FWS and Breaks On Behaviour** - Three measures were used to determine the level of drowsiness. One measure was the subjective ratings provided by the drivers themselves. The two objective drowsiness measures were derived through video analysis. These were the PERCLOS method and frequency of eye-closures. The results from these measures are presented graphically to allow for comparative evaluations in their ability to detect changes in driver drowsiness levels throughout the drive and around breaks. The control group and FWS driver data are presented in figures 1 and 2.

Figure 1 presents changes in mean eye closure frequency around breaks, from seven minutes prior to the break to 12.5 minutes following the end of a break. These time values were derived by determining where most changes occurred for most drivers. Information for all breaks for all drivers were averaged for the Control and FWS drivers for the Baseline and Test sessions. For the Control group drivers (full circle and open triangle) there was a decrease in eye-closure frequency especially during the Test session which then returned within minutes to pre-break levels. For drivers in the FWS group (full square and open diamond), there was a slight decrease in eye-closure frequency following breaks. The impact of breaks on drowsiness assessed by eye-closure behaviour are minimal and highly variable.

Figure 2 presents changes in drowsiness derived through video analysis by applying the PERCLOS method. The curves show that drivers in the Control group, within both sessions, show moderate drowsiness levels and that this level decreases markedly following a break. Following the end of a

break, drowsiness level increased monotonically and returned to pre-break levels after about 12.5 minutes. This result also holds for FWS drivers during the baseline session. However, the pattern of results is different for FWS drivers within the Test session. From the data in Figure 2, we see that the open diamond curve is higher than the other curves prior to the break. The FWS drivers during the test session demonstrated significantly higher levels of objective drowsiness just prior to the break relative to their baseline levels (FWS-Test vs. FWS-Baseline;  $t(4)=2.96$ ,  $p<0.04$ ) and relative to drivers in the control group (FWS-Test vs. Control-Test:  $t(4)=2.56$ ,  $p<0.06$ ; FWS-Test vs. Control-Baseline:  $t(4)=3.24$ ,  $p<0.03$ ).

In summary, for drivers in both groups, across both driving sessions tested, breaks had virtually no impact on drowsiness when measured by eye-closure frequency. The impact of breaks in reducing objective drowsiness level, when measured by the PERCLOS method is evident for drivers in both groups within both test sessions. Drowsiness levels were noticeably higher prior to a break for FWS drivers during the test session when measured using the PERCLOS method. The beneficial effects of breaks on drowsiness level appears to have lasted approximately 12 minutes.

The effects of the signal produced by the FWS on drowsiness levels was assessed with all measures. Within close proximity in time surrounding FWS signal presentation there were no changes in drowsiness levels in any of the subjective of objective measures of driver fatigue.

A different level of analysis of the impact of FWS on break taking behaviour and on objective and subjective measures of drowsiness is possible by studying individual behaviour patterns. As expected for the Control group of drivers, in the absence of FWS, drowsiness levels and break taking behaviour were similar within both sessions. For FWS drivers, observed behaviour within the Test session can be classified into three categories: drivers receiving no drowsiness signals, drivers receiving a moderate number of signals, and drivers receiving a high number of signals. Given this variability, only individual comparisons within each category may be possible to determine the similarities and differences in behaviour within the same experimental condition associated with similar levels of FWS frequency. Consequently, to provide the full range of behavior plots of drivers from each category will be presented.

Within the FWS group, three drivers did not receive a warning signal, although the system was active. During the test session, these drivers did not meet the necessary criteria for signal presentation. Figures 3, 4 and 5 present subjective and objective drowsiness data for three drivers who did not meet the criteria for activating the FWS during the test drive. There was a slight increase in objective drowsiness level as a function of increased drive time with breaks associated with decreased objective drowsiness levels. Early breaks were associated with smaller magnitude decreases in the PERCLOS drowsiness values while breaks taken later in the drive were

associated with a larger impact on objective drowsiness. This pattern is apparently independent of the number of breaks taken.

Similarly subjective drowsiness scores exhibited a monotonic increase in drowsiness level as a function of drive time. For these drivers, breaks had only a comparatively small impact on decreasing reported drowsiness level that lasted for a few minutes.

Figures 6 to 10 show the frequency of FWS signals as a function of time as well as the PERCLOS drowsiness ratings. Blank rectangles indicate voluntary breaks while filled rectangles indicate cone hit induced breaks. In figures 6 and 7 the distribution of drowsiness signals is flat indicating that the frequency of signals does not increase with time on task. Data from the driver in figure 6 show PERCLOS scores increased early in the drive and then remained at a relatively stable level which mirrors the drowsiness signal distribution. There is a noticeable decrease in PERCLOS values following the end of each break. In figure 7, the subjective drowsiness values increased gradually throughout the drive and breaks had only a minor impact in decreasing subjective drowsiness levels. Data from a second driver are presented in figure 8 where PERCLOS drowsiness values increased in discrete steps that tend to follow the drowsiness signal pattern. From data in figure 9, there was a marked increase in subjective drowsiness level following approximately one hour of driving. This was followed by a cone hit. Subjective levels of drowsiness remained stable throughout the remainder of the drive.

Figure 10 presents objective drowsiness levels derived using PERCLOS method for subject 12. The changes in objective drowsiness level paralleled changes in the frequency of warning signals. Sudden increases in PERCLOS values were followed closely in time by either a cone-hit induced break or by a voluntary break.

In summary, voluntary breaks had only a minor effect on reducing subjective and objective levels of drowsiness in drivers during night time driving. Whatever effect there was lasted approximately 12 minutes. Analysis of individual warning signal patterns demonstrate that the FWS did not impact drowsiness levels or induce drivers to take a break. A rapid rise in objective drowsiness seen with the PERCLOS method was usually followed by a voluntary or an imposed break.

## DISCUSSION

The results do not provide unequivocal evidence for behavioural adaptation to FWS. A more accurate description of the results would be that FWS signals were disregarded by almost all drivers. However, one intriguing result was that drivers in the presence of an active FWS show higher objective fatigue levels just prior to a break. Such a result is consistent with behavioral adaptation to FWS. However,

FWS signals were not found to have an impact on driving time, on the propensity for drivers to take breaks, on the number of breaks taken, or on break duration. Additionally, the results demonstrate that breaks were an ineffective countermeasure in decreasing driver fatigue. Breaks had a minor impact on driver fatigue which lasted only a few minutes. However, voluntary and involuntary breaks appeared to be consistently preceded by sharp increases in objective fatigue levels assessed using the PERCLOS method. Each finding is discussed in turn below.

Warning signals were not found to impact objective and subjective fatigue levels or break taking behaviour. It should be stressed that there were large individual differences in the distribution of warning signals presented. Four drivers (a quarter of the sample) failed to meet the established criteria to receive a warning signal. Most of the remaining drivers received a moderate number of warning signals and a few drivers received both frequent and numerous warning signals. Evidently drivers demonstrated large individual differences with respect to fatigue reaction under the same driving conditions. The FWS signals failed to prevent the incidence of cone strikes. Driver number 12 struck five cones during the test with the FWS active. In this instance the driver may have used the FWS to continue driving.

Both voluntary and involuntary breaks were associated with minor decreases in objective and subjective fatigue levels. What changes there were lasted only approximately 12 minutes. This finding is consistent with results from published studies reporting the general ineffectiveness of breaks. Voluntary breaks appear to be no more effective than prescribed breaks. Consequently, it is important to inform drivers that breaks, varying in duration within the range seen in the present study, are ineffective in counteracting the effects of fatigue.

Eye-closure frequency has been used in numerous studies to objectively quantify fatigue levels. In the present study it was not found to be a reliable indicator of fatigue level changes in drivers while completing an overnight driving task on a closed track. However, objective fatigue as determined by the PERCLOS method did seem to be at least as reliable and valid as subjective measures of fatigue. Breaks were shown to be regularly preceded by sharp increases in the PERCLOS ratings. No corresponding sharp increases in subjective fatigue levels were seen. Subjective fatigue levels increased monotonically and gradually with time on task. The PERCLOS method of fatigue assessment seems to tap into changes in driver drowsiness levels that may require intervention. It is necessary to determine the mechanism underlying the different relations between subjective fatigue level and time on task and the PERCLOS method and phasic changes in driver fatigue. Is it the case that there is one absolute threshold beyond which drivers are very likely to stop? Or, is it the magnitude of the relative change from baseline that triggers the behaviour? Furthermore, does the

knowledge that an FWS is active, increase the change needed to trigger a stop? Speculatively, the large individual differences reported may indicate that relative change appears to be more important than absolute level in the subjective assessment of individual driver fatigue. Consequently, what may be necessary is the development of a process to establish a baseline for each driver, and to intervene when a specified percentage change is reached. For example, values derived using The PERCLOS method may be a possible candidate measure.

Although drivers may not be consciously aware of the sharp increase in objective fatigue level, it does seem to be associated with break taking a break or striking a cone. It may therefore be superfluous to have drivers receive signals without apparent meaning, since the physiologically based changes represented by the driver's ocular and facial features seem to be more closely related to break taking behaviour. It may be necessary to render the process by which an objective assessment of fatigue is made more explicit to the driver, to make them aware sooner that they may need to stop driving. For example, if drivers can be made explicitly aware that their eyes are closing for prolonged periods of time while driving, rather than only presenting a signal, may be a necessary step in the decision process to stop driving (see Brown, 1994).

## SUMMARY & CONCLUSION

In summary, the results demonstrate the ineffectiveness of FWS in changing overt driver behaviour. Drivers generally ignored the FWS signals received. The physical aspect of the warning signals used in the present study had no impact on driver fatigue levels. Voluntary rest stops, lasting on average 30 minutes, had a minor impact on decreasing driver fatigue and the effects were short lived. Therefore, voluntary breaks appear to be ineffective in substantially counteracting the effects of fatigue associated with prolonged night time driving. With respect to the dependent measures used in assessing fatigue, eye-closure frequency was not clearly associated with changes in driver fatigue levels. Subjective fatigue values were associated with tonic (e.g., slow) changes in fatigue levels, whereas values derived using the PERCLOS method were associated with phasic (e.g., quick) changes in fatigue levels. The latter fatigue assessment method seems more promising as an on-line index of critical fatigue levels in drivers requiring intervention.

Future research needs to address what mechanism induces subjects to take breaks and ignore warning signals. One hypothesis is that drivers consider the signal redundant. Also, given that drivers perceive only slight decreases in their fatigue level that last a few minutes following a break, drivers are not inclined to stop and prolong the drive (cost) for a minimal improvement (benefit) in their state. This may have been a greater factor in the present study given the presence of a safety observer. Such factors reduce the effectiveness of

FWS. Given the present findings, more research into the consequences of implementing FWS in vehicles is necessary prior to their general implementation.

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**Table1**  
**Summary Information for Drivers in Control Group**

Subject	Session	Distance Driven (km)	Test Duration (min.)	Driving Time (min.)	Hours Slept	Sleep Quality
1	Base	332.2	297.9	284.6	7.3	85
	Test	351.1	320.0	313.0	8.0	90
2	Base	331	321.2	279.6	7.0	75
	Test	344.8	356.2	288.8	7.0	90
3	Base	234.3	336.1	279.5	7.3	85
	Test	292.8	358.5	278.1	6.3	50
4	Base	350.3	297.8	275.1	3.8	60
	Test	314.5	292.3	266.0	6.8	40
5	Base	347.5	329.4	306.5	4.8	75
	Test	248.4	325.0	---	7.5	75
6	Base	262	242.3	225.8	4.5	95
	Test	296.8	278.0	258.0	7.5	90
7	Base	345.6	308.0	292.4	8.5	80
	Test	351.7	336.2	305.5	9.0	90
8	Base	344.6	304.0	304.0	6.5	90
	Test	302.7	337.3	337.3	7.3	90

Subject	Session	Distance Driven (km)	Test Duration (min.)	Driving Time (min.)	Hours Slept	Sleep Quality
	Base	344.6	285.9	285.9	7.0	70
	Test	180.2	175.0	155.0	6.3	60
10	Base	234.5	231.0	209.1	6.8	70
	Test	283	268.5	252.4	6.0	55
11	Base	344.9	328.6	298.1	7.5	95
	Test	344.9	309.4	294.8	5.0	90
12	Base	344.5	330.0	293.9	5.5	70
	Test	296.4	335.2	295.8	8.0	85
13	Base	297.9	364.0	249.3	3.3	60
	Test	352.6	353.9	301.0	6.5	80
14	Base	345.5	321.4	321.4	7.3	70
	Test	345.9	334.4	328.8	7.0	70
15	Base	350.7	335.0	315.0	6.5	95
	Test	350.8	317.0	298.4	8.0	---
16	Base	332	354.7	316.3	6.5	55
	Test	351.2	368.0	335.5	7.3	65

Note: High sensation seekers are shaded.

**Table 2**  
**Summary Information for Fatigue Warning System Group Drivers**

Subject	Session	Distance Driven (km)	Test Duration (min.)	Driving Time (min.)	Hours Slept	Sleep Quality
1	Base	352	325.5	317.3	1.8	40
	Test	345.5	309.9	277.5	3.8	50
2	Base	352	317.3	304.8	7.8	65
	Test	344.8	336.5	299.1	6.3	75
3	Base	344.6	293.2	293.2	8.0	80
	Test	344.7	320.2	307.3	8.0	70
4	Base	332.3	328.3	---	7.7	85
	Test	198.7	321.6	301.7	7.3	70
5	Base	349.9	311.4	306.1	8.8	60
	Test	352.2	341.4	316.3	6.8	50
6	Base	338.9	393.0	283.9	6.8	50
	Test	226.7	288.2	193.6	6.3	70
7	Base	351.4	348.0	313.1	5.5	70
	Test	351.9	326.5	318.7	5.3	65
8	Base	342.3	332.7	310.3	8.0	95
	Test	352.2	351.7	317.5	8.0	75

Subject	Session	Distance Driven (km)	Test Duration (min.)	Driving Time (min.)	Hours Slept	Sleep Quality
9	Base	346	308.0	265.0	8.0	90
	Test	350	305.0	270.0	7.3	90
10	Base	345.2	316.3	313.5	7.3	70
	Test	345	294.2	286.2	6.8	70
11	Base	221.2	305.3	191.0	5.0	50
	Test	344.3	376.3	295.9	7.8	90
12	Base	239.9	315.1	267.0	6.3	70
	Test	303	357.5	271.9	6.5	80
13	Base	351	317.7	306.5	6.5	90
	Test	352	315.0	304.0	6.0	80
14	Base	349.5	327.5	313.6	4.5	39
	Test	347.7	336.3	309.0	5.0	45
15	Base	348.2	313.4	298.0	8.3	85
	Test	351.8	309.8	303.1	8.5	90
16	Base	311.2	335.0	297.1	11.0	70
	Test	351.4	356.7	327.1	7.8	70

Note: High sensation seekers are shaded.

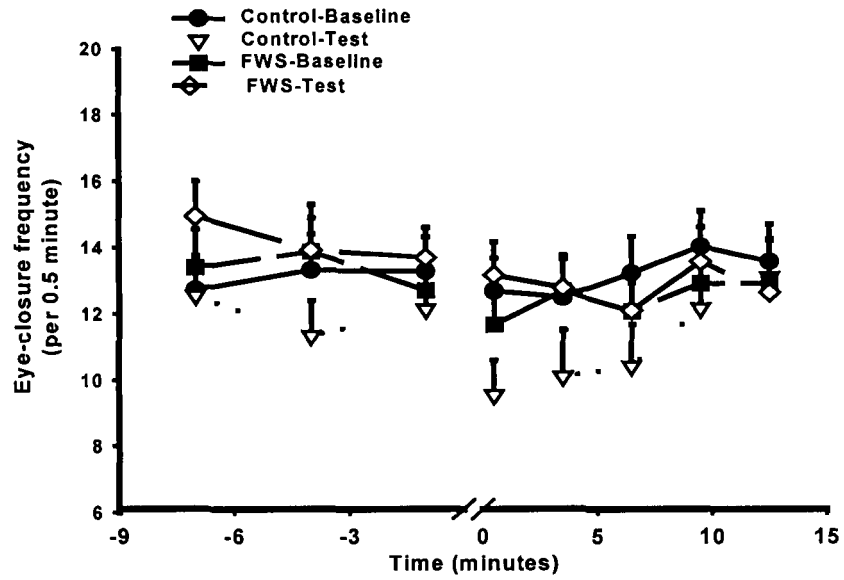


Figure 1. Mean eye-closure frequency as a function of time pre and post break for control and FWS drivers within Baseline and Test Sessions.

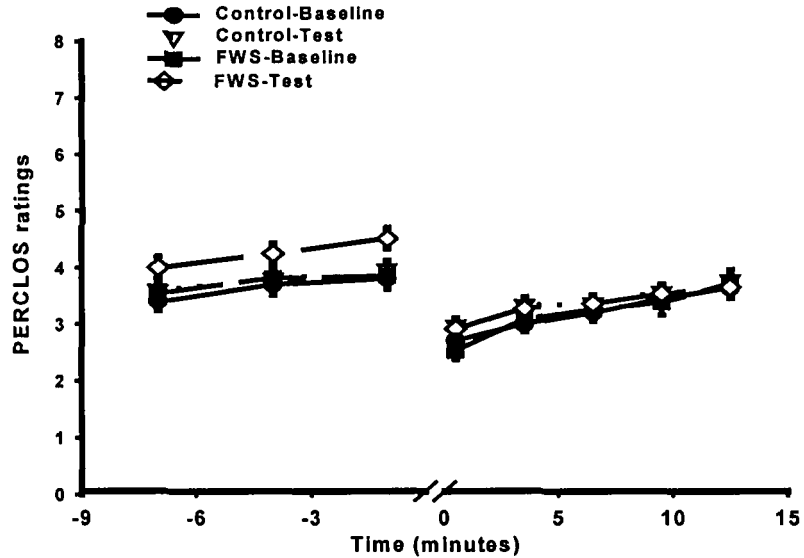


Figure 2. Mean PERCLOS ratings as a function of time pre and post break for control and FWS drivers within Baseline and Test Sessions.



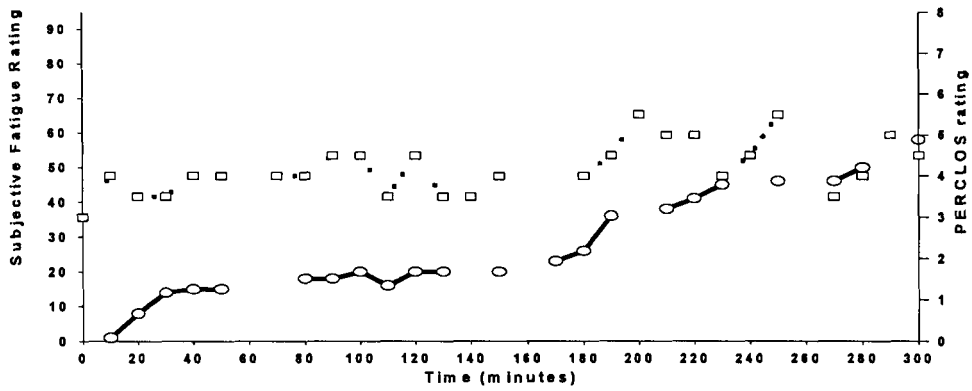


Figure 3. Fatigue ratings using PERCLOS method (dotted curve) and subjective levels (line) as a function of time on task for FWS driver #4 (Test Session).

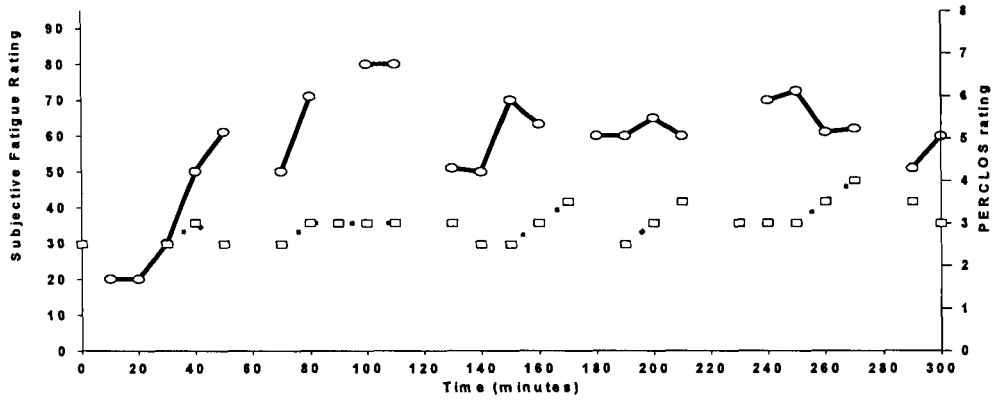


Figure 4. Fatigue ratings using PERCLOS method (dotted curve) and subjective levels (line) as a function of time on task for FWS driver #5 (Test Session).

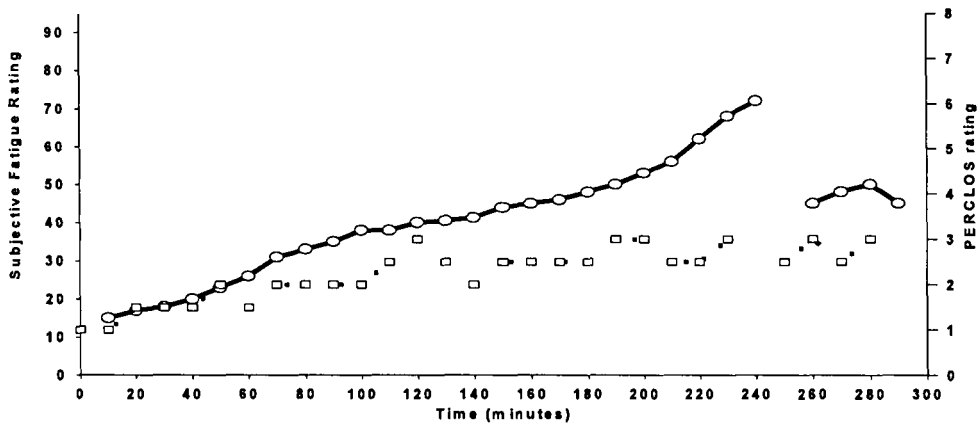


Figure 5. Fatigue ratings using PERCLOS method (dotted curve) and subjective levels (line) as a function of time on task for FWS driver #10 (Test Session).

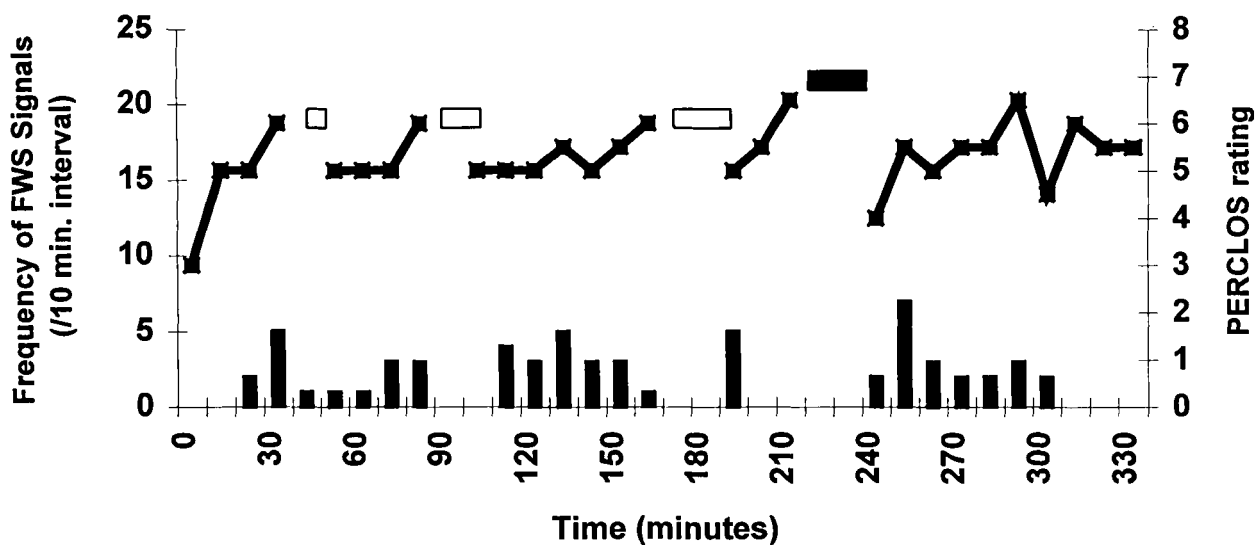


Figure 6. PERCLOS ratings (line) and frequency of FWS signals (bars) as a function of time on task for FWS driver #2 (Test Session).

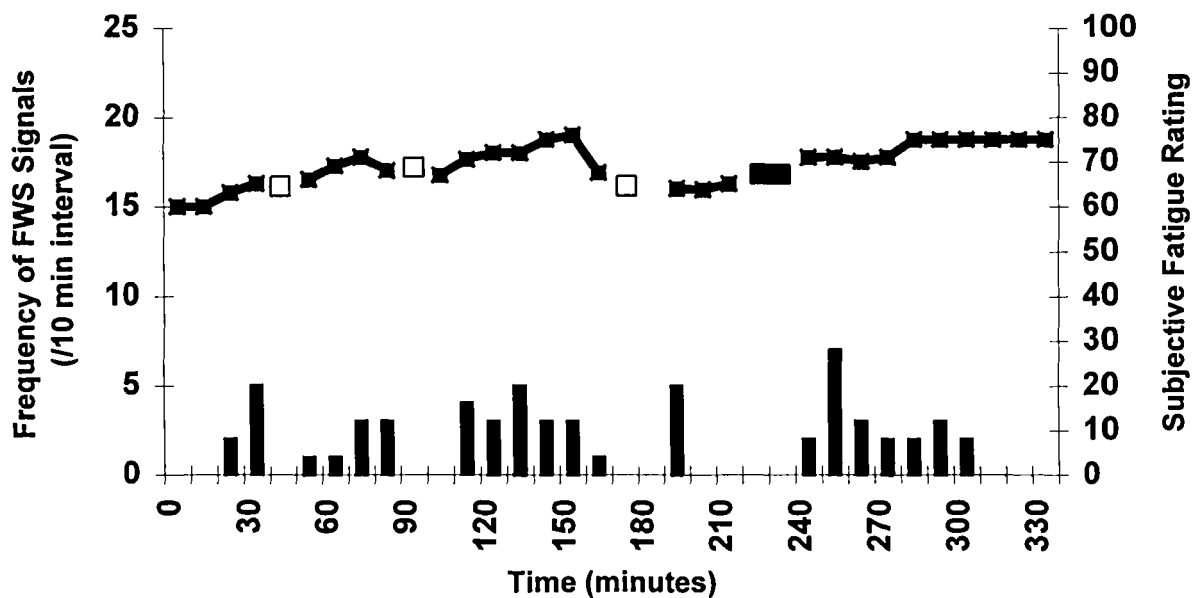


Figure 7. Subjective fatigue ratings (line) and frequency of FWS signals (bars) as a function of time on task for FWS driver #2 (Test Session).

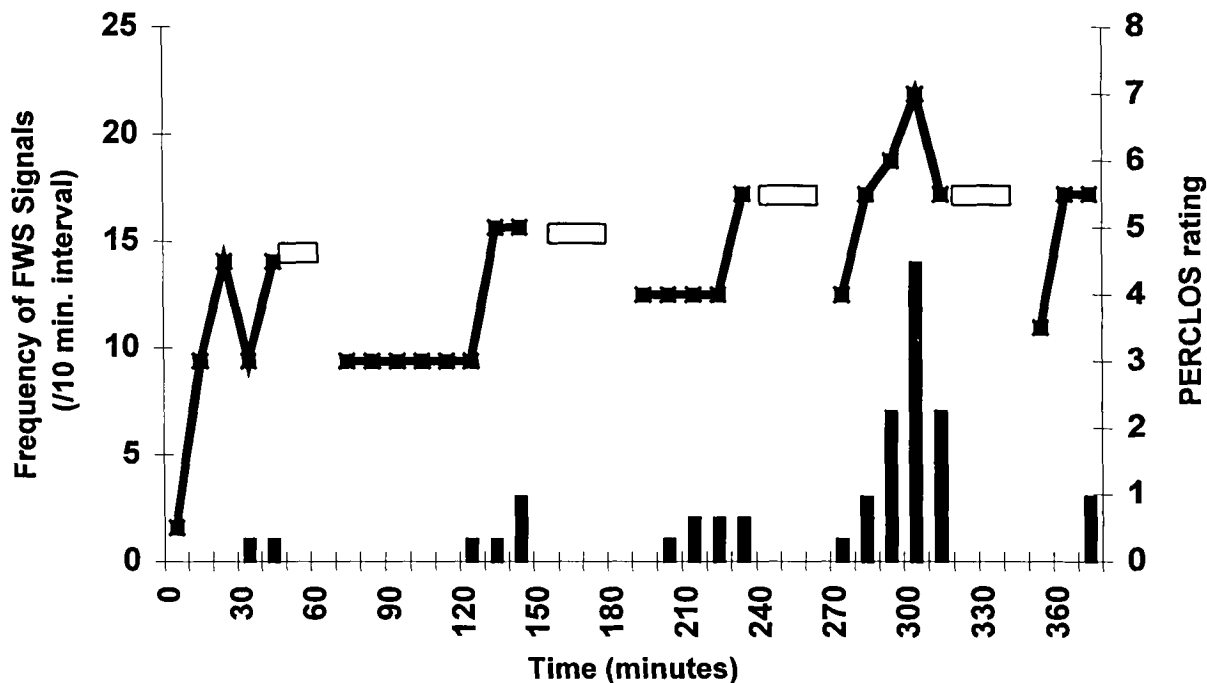


Figure 8. PERCLOS fatigue ratings (line) and frequency of FWS signals (bars) as a function of time on task for FWS driver #11 (Test Session).

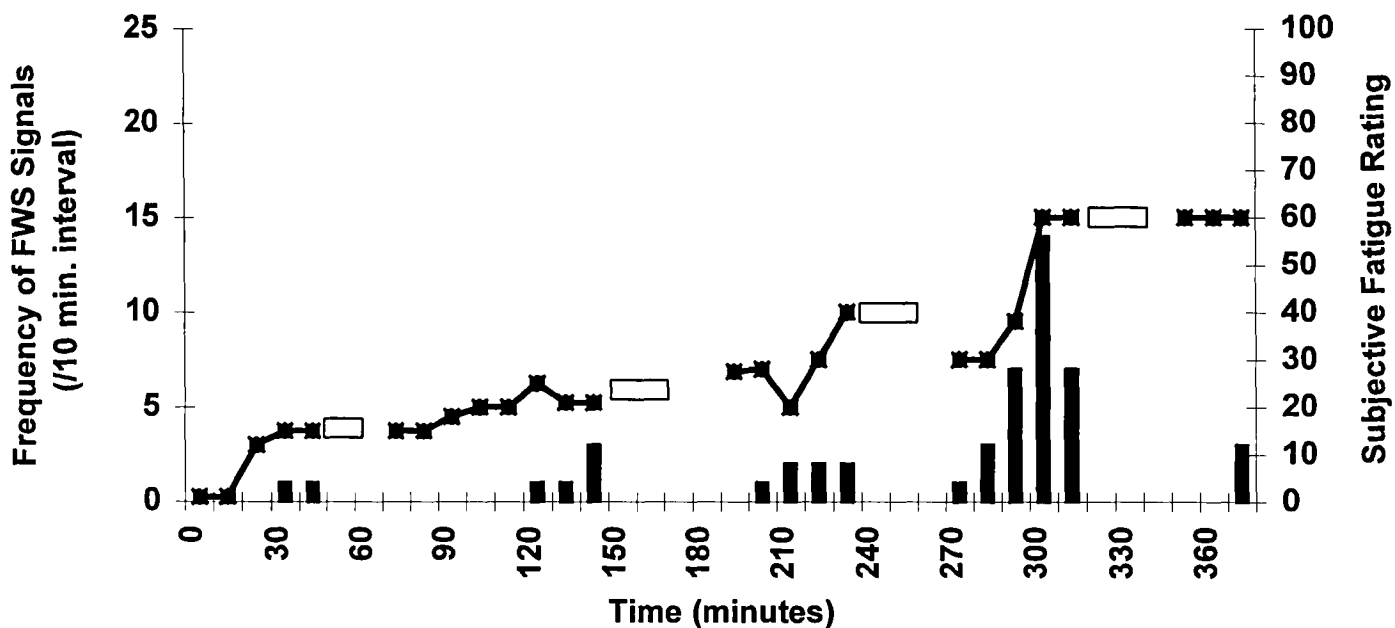
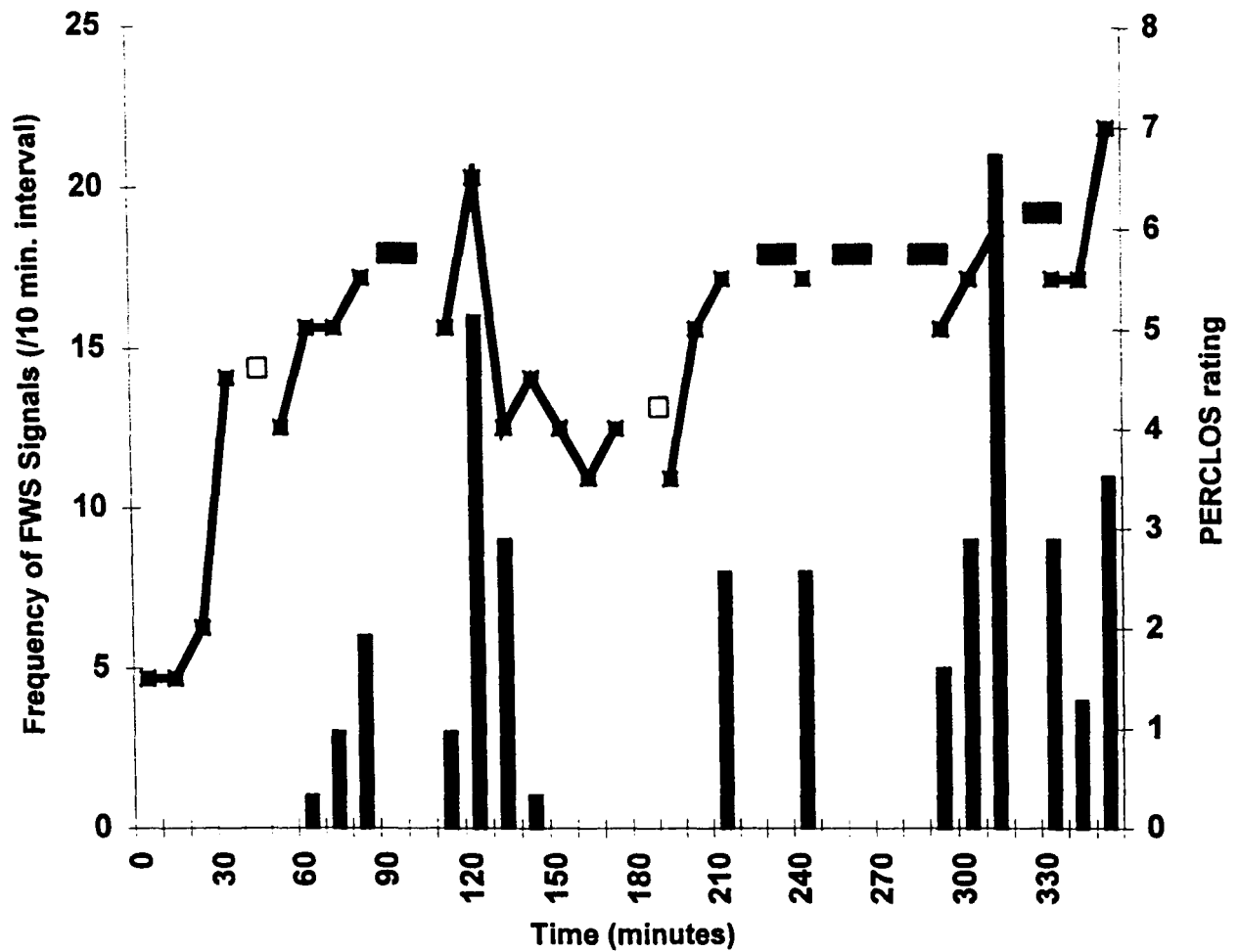


Figure 9. Subjective fatigue ratings (line) and frequency of FWS signals (bars) as a function of time on task for FWS driver #11 (Test Session).



**Figure 10. PERCLOS fatigue ratings (line) and frequency of FWS signals (bars) as a function of time on task for FWS driver #12 (Test Session).**

## VEHICLE DESIGN AND INJURIES SUSTAINED BY FEMALE DRIVERS

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Paper Number 98-S2-P-22

### ABSTRACT

It has long been recognised that male drivers are at greater risk of being killed in a road crash than female drivers. What is less well recognised is that female drivers have a higher risk of being seriously injured in a road crash.

One factor that has been identified as contributing to this trend is that women tend to be less robust than men. Female drivers also tend to sit closer to the steering wheel and this may increase the likelihood of injury in a crash. The issue has taken on greater significance with recent reports of children and small adults, mainly women, killed or injured by the deployment of airbags in crashes.

The current study analysed the factors relating to the seating position of male and female drivers.

### INTRODUCTION

In Australia during 1995, female drivers of cars were 17 per cent more likely than male drivers to be seriously injured in a road crash for every kilometre travelled (FORS Monograph 12). Female driver fatalities also rose in 1995. During 1995, there were 209 female drivers of cars killed on Australia's roads. This represented a substantial increase over the number killed in the previous year (177) and was the highest since 1991 (219). Generally, road crash fatalities have been declining since 1989, so this marked increase in female driver fatalities evident in 1995 was a disturbing trend.

A similar trend has been noted in the United States of America. The US Department of Transportation's National Highway Traffic Safety Administration released a report in 1994 which found that the risk of being fatally injured has been increasing for female drivers.

Another important consideration is the relative physical robustness of men and women. Female drivers are more likely to be killed or seriously injured than male drivers in crashes of equivalent severity. Thus some of the apparent levels of risk may relate to their vulnerability rather than their actual driving behaviours.

In the USA, Evans (1991) has suggested that between the ages of 15 and 45, women are 25 per cent more likely to be killed than men when subjected to the

same physical impact. Evans also cited Foret-Bruno who compared injury outcomes for similar severity crashes, finding that women were around 20 per cent more likely to be injured than men.

Part of the greater vulnerability of women could be that they tend to sit closer to the steering wheel than men and the chance of a head strike is greater. The introduction of airbags has added a new dimension to the problem. There have been incidences of children and small adults being fatally injured by airbag deployment, in part due to their proximity to the airbag, which in the case of drivers is located in the steering wheel. A number of authorities, including the Federal Office of Road Safety, have issued warnings on the danger of sitting too close to the steering wheel (FORS Monograph 13).

Parkin, Mackay and Cooper (1993) have shown that women do indeed sit closer to the steering wheel than men and are therefore more prone to head strikes. Parkin et al did not investigate possible explanations for the observed difference in sitting distance. The current study considered a number of issues. Is the observed difference a genuine sex difference? If women drive smaller cars than men, do they sit closer because of the smaller occupant space of the vehicle? Or is the difference related to physical size of the individual so that, in fact, the observed difference is not one of sex but rather one of physical size? If the observed difference is due to physical size, is the length of the arm more important than the length of leg or vice versa?

### METHOD

#### Design

The research involved measuring the driver's position in the car and driver characteristics such as sex, weight, height, length of leg, length of upper arm and length of lower arm. The model of car was also recorded.

#### Sample

Data were collected by volunteer students of the University of Newcastle from 300 drivers in the car parks of popular shopping centres in Newcastle, New South Wales. Participants were stratified by the size of the car they were driving and sex. Table 1 has details.

**Table 1.**  
**Sample size by characteristics of drivers.**

	Male driver	Female driver
Small car	50	50
Medium car	50	50
Large car	50	50

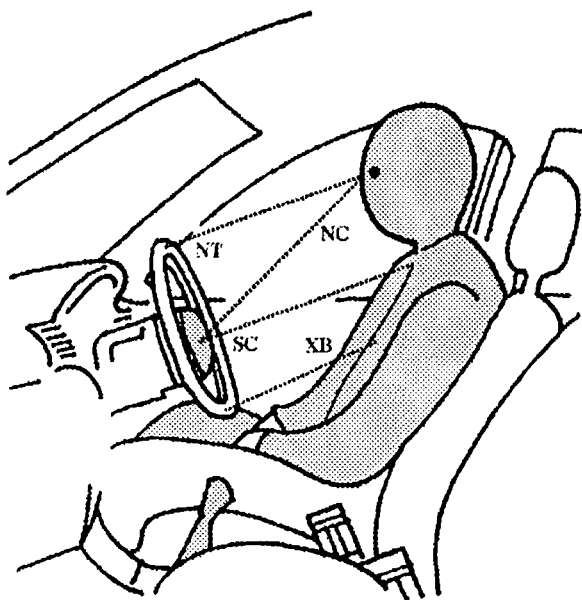
Drivers were approached to participate in the study. They were asked to sit in a normal driving position and measures were taken with a tape measure. The driver's weight was recorded on the basis of self report.

#### Measures

The distances measured in the study are illustrated in Figure 1. All distances given are in centimetres. Weight is in kilograms. Distances measured included from the nasion to the top of the steering wheel (NT), from the nasion to the centre of the steering wheel (NC), from the sternum to the centre of the steering wheel (SC) and from the xiphisternum to the bottom of the steering wheel (XB).

The driver's height (H), weight (W), length of upper arm (UA), length of lower arm (LA), and length of leg (L) were also recorded.

**Figure 1**  
**Measures of distance of driver from the steering wheel.**



## RESULTS

Analysis confirmed that men and women differed on most of the attributes measured in the study. Table 2 has details of means, standard deviations (SD) and statistical significance (*p*-value of *t*-test). Figures 3-5 plot distance from the steering wheel by percentiles for male and female drivers.

**Table 2**  
**Comparison of male and female drivers.**

Measure	Male drivers		Female drivers		<i>p</i> -value
	Mean	SD	Mean	SD	
H	178.1	7.3	164.6	7.3	.001
W	77.0	11.7	65.0	13.2	.001
UA	32.2	3.2	30.5	4.2	.001
LA	25.4	3.6	23.1	2.3	.001
L	51.9	5.5	48.6	4.7	.001
NC	51.0	4.7	46.4	4.9	.001
NT	48.6	5.2	44.0	5.1	.001
SC	50.0	4.8	45.1	5.4	.001
XB	30.5	5.4	27.4	5.6	.001

Male drivers are taller, heavier, have longer limbs and sit further from the steering wheel than female drivers. All these differences are significant at  $p < .001$ . The difference of 4.6cm for NC is comparable with the difference of 5.2cm found by Parkin, Mackay and Cooper (1993).

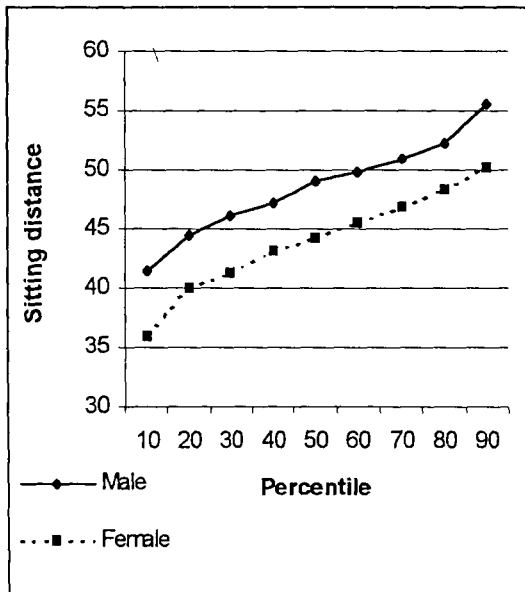
Analysis of vehicle size, driver characteristics and sitting distance from the steering wheel is given in Table 3. Drivers of larger cars tended to sit marginally closer to the steering wheel than drivers of smaller vehicles. ANOVA results confirmed that these differences were significant for NC, SC and XB. The results for NT were in the same direction but did not reach statistical significance. Drivers of larger vehicles tended to be heavier than drivers of smaller vehicles. There was no statistically significant difference in height.

**Table 3**  
**Vehicle size, driver characteristics and average distance of driver from the steering wheel.**

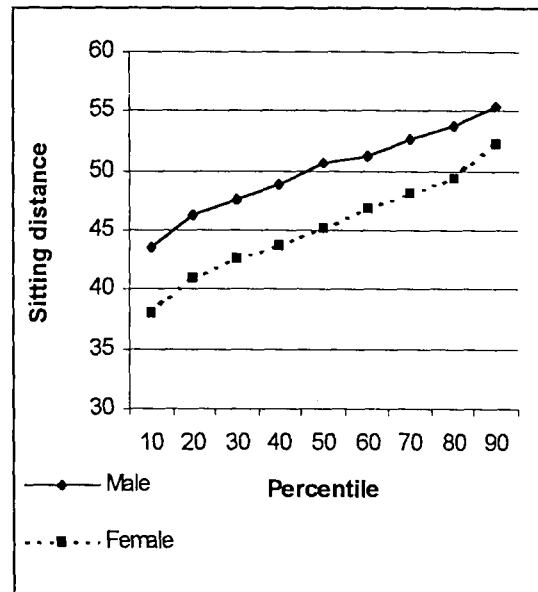
Measure	Small car	Medium car	Large car	<i>p</i> -value
NT	47.2	46.0	45.8	.150
NC	49.7	48.7	47.8	.048
SC	48.8	47.6	46.4	.012
XB	30.1	28.6	28.1	.037
H	171.7	171.6	170.7	.716
W	69.9	68.5	74.7	.004

The variables of interest were entered into a MANOVA to test whether sitting distance from the

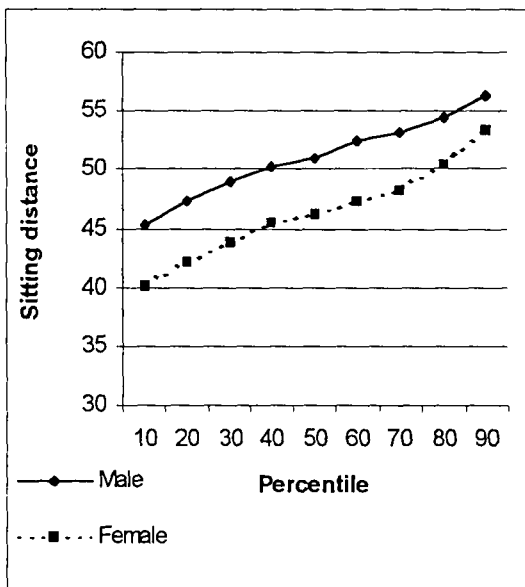
**Figure 2.**  
Distance from nasion to  
top of steering wheel (cms)



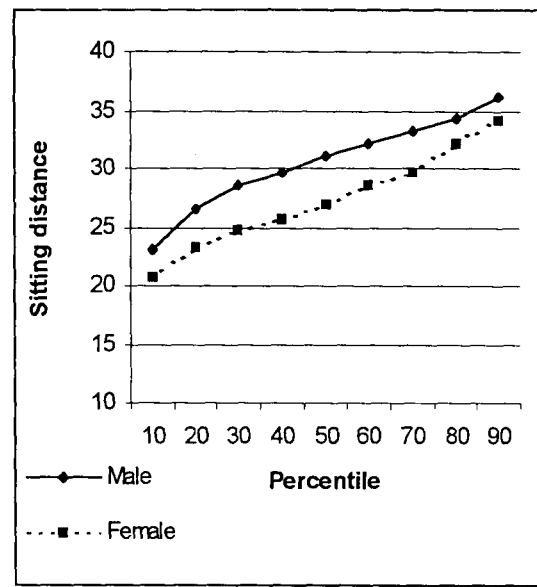
**Figure 4.**  
Distance from sternum to  
centre of steering wheel (cms)



**Figure 3.**  
Distance from nasion to  
centre of steering wheel (cms)



**Figure 5.**  
Distance from xiphisternum to  
bottom of steering wheel (cms)



steering wheel was related to sex and vehicle size when the physical characteristics of the driver were taken into account. NC, NT, SC and XB were the dependent variables in the MANOVA with H, W, UA, LA and L, as covariates.

Overall, sex of the driver is not related to sitting

distance from the wheel once the covariates are taken into account ( $p=.495$ ). None of the individual measures of distance had a significant  $F$  statistic. Vehicle size was related to sitting distance ( $p=.034$ ) although only NC and SC had significant individual  $F$  statistics.. The sex by vehicle size effect was not significant ( $p=.841$ ).

In terms of the covariates, it is the height of the driver which is the statistically significant variable. Table 4 summarises the t-value for each of the dependent variables and covariates.

**Table 4**  
**t-value for each of the dependent variables and covariates**

Covariates	Distance from the steering wheel measures			
	NT	NC	SC	XB
L	t=0.4 p=.69	t=0.1 p=.94	t=1.2 p=.23	t=0.3 p=.80
UA	t=1.1 p=.29	t=0.8 p=.45	t=-0.8 p=.40	t=-0.3 p=.76
LA	t=1.0 p=.32	t=0.2 p=.85	t=1.4 p=.16	t=2.5 p=.01
H	t=6.2 p=.00	t=7.5 p=.00	t=7.1 p=.00	t=7.4 p=.00
W	t=0.3 p=.75	t=1.1 p=.27	t=-0.1 p=.86	t=-3.7 p=.00

With respect to measures of the distance of the head (NC, NT) and sternum (SC) from the steering wheel, observed differences between male and female drivers can be accounted for by height, and, in fact, no other covariate is significantly related. The results for XB suggest that height, weight and length of the lower arm are significant covariates.

## DISCUSSION

The major finding of this study suggests that seating distance from the steering wheel is a function of the driver's height rather than the driver's sex. Men and women of similar height sit at a similar distance from the steering wheel. This is an important finding because it suggests that the debate over the appropriate parameters for dummy placement in crash tests should relate to the height of the driver population rather than its sex composition. This is not to deny that women are disadvantaged by a practice which sets the test parameters at those relevant to the 50<sup>th</sup> percentile male driver but this disadvantage is due to the fact that women, on the whole, are shorter than men. It is not being a woman per se that is the issue.

In light of this, warnings about sitting distance in vehicles fitted with airbags, such as that issued by the Federal Office of Road Safety (FORS Monograph 13, 1996), should not necessarily single out women. All short drivers are at a greater risk and the message might be better directed without reference to the sex of the driver.

This finding is also important because it suggests that driver height may be a reasonable approximation

for sitting distance from the steering wheel. The use of this surrogate variable could be of value in road crash research or vehicle design development related to driver seating position.

Finally, this finding implies that, as height is rather inflexible, it may not be an easy task to design a vehicle so as to maximise sitting distance from the steering wheel. For very short drivers, there may even be an argument that wearing a seat belt is a much preferable strategy to the use of an airbag.

The second finding of the study was that drivers of larger cars tended to sit closer to the steering wheel than drivers of smaller cars. The reasons for this are not clear. Larger cars tend on the whole to have more backward space for seat adjustment and one might expect that this would imply that drivers of larger cars might sit further from the steering wheel.

While there was no significant difference in the height of drivers by vehicle size, the drivers of larger vehicles tended to be heavier than the drivers of smaller vehicles. This could well explain the significant results for SC and XB where body girth would influence the measurement. It does not explain the significant finding for NC. This measure, however, was of borderline significance and given the lack of significance for the associated measure NT, perhaps some doubts remain as to the robustness of this finding. It may simply be that larger people drive larger cars and their girth will influence some measures of sitting distance from the steering wheel.

## ACNOWLEDGEMENTS

I am indebted to A Dobson, WJ Brown and J Ball of the Research Institute of Gender and Health, University of Newcastle for their assistance in the design of the study and the collection of the data, and to A Ellis and Clare McFadden for their design work.

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## **VISUAL PERFORMANCE DURING NIGHT DRIVING**

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Paper Number 98-S2-P-23

### **ABSTRACT**

Driving by night is known to be more dangerous than during daytime. In addition, a lot of drivers complain about vision during night driving. This is the first cause of driving restriction for seniors.

The needs for lightning systems improvement concern safety and comfort. This relies on a certain knowledge about visual performance of the driver.

The characteristics of the visual environnement of night driving and the physiology of vision at low photopic luminance level give clues to the improvements to reach. A specific experimental set-up is developped in ordrer to measure the visual performance and fatigue while driving and without interrupting it. This test is based on the measure of visual acuity and contrast sensitivity. The visual fatigue is estimated from the evolution of the results to the tests versus time.

Average drivers are asked to drive at early night (avoiding drowsiness) on open roads in order to compare several frontlight systems. Experiments lasted 3 hours of driving. Each driver tested three lighting systems, and then drove 9 hours in three nights.

A classification of the systems is obtained in terms of visual performance of the drivers.

### **INTRODUCTION**

Driving by night is a distinctive and non-physiologic situation that induces numerous accidents. In France, it represents 20% of traffic but it provoks 50% of death. Actually, night driving has many sights starting from casual driving to professionnall and continuous night driving of lorries. Many factors can have an influence upon night driving :

- atmosphere (monotony, repetition, tiredness, ...)
- toxicology (alcohol, tobacco, drugs, ...)
- vision (visual performance, glare sensitivity, optical illusion, ...)
- psychology (euphoria, fear, ...)

From an ergonomic approach, night does not exist by itself. In fact, it is a mental representation, specific for each person, linked to the weak performance of his senses, his visual potential and his psychological background. As human is blind at night, he cannot build his own previous experience of that kind of vision. Thus, each night image is immediately convert then interpreted

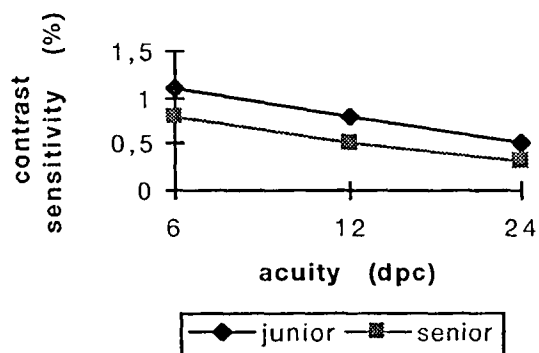
as a daylight image following a complex conversion scheme. The pertinency of this transformation straightly relies from previous experience of the driver ; insofar as visual function is defined as being a psychophysiological feeling acquired deriving from a previous experience. Then, it is possible to consider that the night driver with his frontlight system has a lowered photopic vision and not a enhanced night vision and all the lighting systems have been made in order to bring night vision closer to daylight vision.

Improvements of front-light systems become important in terms of quality and intensity of light, shape of the beam. A better knowledge about vision during night driving is needed concerning safety and front-light improvement. Experiments on open road, with ordinary drivers, testing pertinent visual indicators are an approach to some of these problems.

## Methodology

The complexity of the visual system pulls the experimental set-up. It starts with the eyes and ends in specific areas of the brain. Vision results from an optical processing, a transform from light waves to nerve impulse, then parallel processes for pattern, movement and colour recognition all referring to memory informations. Any change in the luminance of the scene induces modifications in the first optical stimulation and in all the processing. The visual system adjusts continuously to the luminance, the distance to objects, ... Then, any attempt to evaluate the visual performance of someone in a defined situation (i.e. a driver) will be significant only if the subject don't have to adjust his vision in terms of luminance nor of distance and if he don't have to interrupt his actual task (i.e. : driving).

Many parameters can be measured concerning vision. Acuity versus contrast is known to be very sensitive to the luminance level, to the age of the subject and to his fatigue. Many studies have been done in hospital or laboratories environments and also for ergonomic purposes (Gur, 1992 ; Kluka, 1993 ; Koskela, 1998 ; Quant, 1992 ; Phillips, 1992). The subject is asked to look at a network or series of letters or symbols (Landolt rings or Snellen E) of variable sizes, drawn in a scale of gray levels generally over a white background (other way a black background). The contrast sensitivity function is the limit of visible contrast for all spatial frequencies (fig 1.).



**Figure 1. contrast sensitivity function for both junior and senior population at 200 cd/m<sup>2</sup>.**

Driver's visual performance is correlated to the luminosity of the observed scene, the contrast of scene's targets and driver acuity. For this reason, the sensitivity contrast function test to control visual performance during experiences seemed to be a suitable starting point for the driver vision evaluation.

The main difficulty of such experiments concerns the adaptation of a pertinent visual test in driving context, without any perturbation for the driving task. Results in laboratories context must be transposed in a real car context. First, driver's vision has to be evaluated in laboratory environnement in order to detect

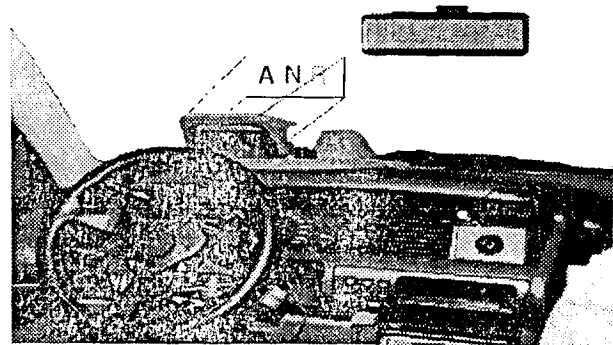
possible pathology and to check that the driver has a correct vision versus his age and others physiological parameters. All the drivers who participated to the experiments had a standard vision (with or without glasses) without any pathology except presbyopia for seniors.

The standard visual test uses networks with constant acuity at decreasing contrasts. For safety reason, only still images could be projected in front of the car. Letters were preferred to symbols because they involved a identification/recognition process and not only detection, that is closer to the driving task. In order to avoid luminance adjustment, the background of the test had the luminance of the road surface lightened by the low beam of the car. The contrast levels were calculated from this background. This luminosity corresponded to a low photopic level. The delay of answers was never measured as it also relies on traffic conditions.

The integration in the car is made within a Head Medium Display, without helmet, which showed letters generated by a display (fig2). The path of light was controlled by mirrors, strip and which ensured a projection at 1.8 meters from the driver's eyes. Thus the driver kept in far vision during the test. The image luminosity depended on light intensity of the screen ( $100 \text{ cd.m}^2$ ), coefficient reflection of the mirrors (90%) and strip (4%).

In this field of illuminance the maximal spatial frequency is about 4 Degree Per Cycle (dpc) and looks like a bandpass filter. For display size reasons, only spatial frequency beginning from 3 dpc could be studied. To have a good representation of the contrast sensitivity function, four spatial frequencies between 3 and 24 dpc were measured. This range, integrating visibility and lisibility, is important because useful in a driving context. The thresholds of contrast were between 0.8 and

6% corresponding to known contrasts detected at identical luminance.



**Figure 2. Experimental set-up : Letters of decreasing contrast projected via a head-up display.**

Practically, letters of the same size but of decreasing contrast are displayed at the same time. The driver is asked to read loudly what he sees. Two series of four sizes of letters are shown without interrupting the driving.

## Visual fatigue

### Protocol

10 ordinary drivers, aged under 40 years, with correct acuity (10/10) were selected after undergone an acuity clinical control. To avoid drowsiness, experiments held in winter and each driver was asked to drive at early night on open roads (motorways and trunk roads) in order to compare three front-light systems. The journey lasted three hours. Four spatial frequencies were recorded and repeated twice to ensure statistical interpretation. The recording was realised every 45 min. The evolution of the contrast sensitivity function can be interpreted as a visual fatigue indicator.

Each driver tested only one front-light system a night and waited about two weeks the next experiment.

The devices differed by their luminance (689 cd/m<sup>2</sup> ; 1552 cd/m<sup>2</sup> ; 6325 cd/m<sup>2</sup>).

Driver behavior is estimated by measures on the car, and physiological measures. Each driver, had to answer a questionnaire about perception of the beam, for every front-light system. Only the visual aspect is presented here.

### **Results from the contrast sensitivity function**

First, the driving task was not perturbed and the test was well accepted by the drivers. The contrast sensitivity function could be established at any time with homogeneous results with regards to the reference in laboratory.

No statistical difference between two measures for every spatial frequency was shown : this prove that the number of measures taken was adequate.

During driving, no evolution of the contrast sensitivity function could be observed, thus, there was no degradation of visual performance for a long night drive, whatever the front-light system used.

The perception of the contrast classified the light systems, whatever the spatial frequency tested. However, the frequency 6.08 dpc was the less discriminant. The results were correlated with the luminance of front-light system.

Global visual performance was also measured using a Ergovision from Essilor before and after the journey. The Ergovision is of commun use in occupational medecine. Results were correlated to those in laboratory but no effect of the front-light systems could be noticed as the driver visual system adapted to the luminance of the Ergovision. This shows the interest of such study in real visual context which avoid problems of estimation about : luminance range, front heads-light illuminance, beam pattern and road reflection.

### **Results from the questionnaire**

Drivers were asked about visual sensation before and after the course, perception of visual fatigue, judgement of beam in staight line and curve configuration.

Each driver performed the test at night after a working day ; but they were not physically tired. However, they felt visual fatigue after the course. This observation could be noticed moretheless for the more luminous light. However, the drivers found comfortable all the devices tested and the only one noted as very comfortable was the most lumincous front light system.

### **Age and night vision**

#### **Protocol**

33 drivers aged between 20 and 40 years, and 27 drivers aged over 55 years were selected to participate to a night driving experiment. Each driver passed an optical clinical control. Only correct acuity vision were accepted to insure good homogeneous of the driver population. The age of 55 years old was decided as the limit for the senior group because presbyopia is then stabilised.

The test consisted of two 20 minutes of night journey on a winding road with correct horizontal signalisation. Half of the drivers first drove with halogen lamps and drove again on the same road with xenon lamps. The other half tested the lamps in the counter order. Since long journey didn't altered visual performance, the journey duration was fixed in function of visual time adaptation to new luminance. At the end of the journey a control of the contrast acuity was realised twice. In order to avoid misunderstanding problems of the test, it was explained and realised before the journey.

For this experiment three spatial frequency between 6 to 24 dpc were controlled, with two front light luminances (halogen : 2162 cd/m<sup>2</sup> ; xenon : 2327 cd/m<sup>2</sup>).

### Results from the contrast sensitivity function

The results confirmed that younger drivers had better acuity than older drivers. However, no difference of acuity could be noticed versus luminance for both populations (fig 1). The increase of luminance of xenon lamps was not sufficient enough to give seniors the same acuity as junior using halogen lamps.

### Results from the questionnaire

Xenon lamps were always estimated as the most comfortable front light system. The sharpened cut-off of xenon lamp was noticed but did not induced any discomfort.

Front-lights were also judged in terms of colour temperature. For this experiment, drivers were more comfortable using higher temperature light (xenon : 3903K ; halogen : 3100K), which was more similar to the natural light. Seniors were less sensitive to the whiter xenon lamps probably because of a decrease of perception of short wavelength lights due to age.

## **CONCLUSION**

Improvement of front-light systems needs, to be efficient, a better knowledge of the links between visual performance and the devices provided. The use of a head-up display to perform ophtalmic tests allows the assesment of in situ visual performance without any perturbation induced by visual adaptation.

## DRIVER BEHAVIOR IN A THROTTLE OFF SITUATION

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Paper Number 98-S2-P-24

### ABSTRACT

166 average drivers were asked to drive along a track at specified speed. The speed was increased at each lap. At 80 km/h one of the bends was sharpened without warning the driver. Three cars were used. They were identical except the handling : one was standard, one oversteering and the last understeering. None of the drivers knew there was several cars and each drove and saw only one car. Even if the drivers didn't know anything about the handling of the car, some differences already appeared in their driving behavior relying on the car dynamic characteristics, even at low speed (50 km/h).

Half of the drivers ran out of the road with the understeering car even if this was the car which gave them the highest confidence (but not necessary the best comfort as they generally felt the « steering wheel was heavy »). The two other cars gave close results and helped more than the two thirds of the drivers to keep on the road.

### INTRODUCTION

Bends are probably the most difficult road parts to drive. Drivers often slow down when they reach a bend whereas they maintain their speed through other road events. Bends are also a frequent location for accidents all the more the severity increases (Table 1).

**Table 1.**  
**Location of road accidents involving at least one car versus severity (ref. LAB)**

	Accidents	Injuries	Deaths
Curve	14 %	22 %	26 %
Straight	50 %	52 %	57 %
Crossing	36 %	26 %	17 %
Total	345 097	105 574	21 821

A quarter of the accidents involve only one car ; they correspond to half the fatal accidents. When considering only single car fatal accidents, crashes almost never occur at crossings but curves are over represented (Table 2).

**Table 2.**  
**Location of fatal single car accidents**  
 (ref. LAB : source fatal accidents in France in  
 1990 ; 13 unknown)

	Crossing	Straight	Curve
Deaths	1 %	39 %	59 %
2273	17	896	1347

Then, before considering sophisticated devices which help the driver to keep the control of his car in critical situations, it is important to study the links between the dynamic characteristics of the car and the driver behaviour, both in normal and critical driving situations.

### Protocol

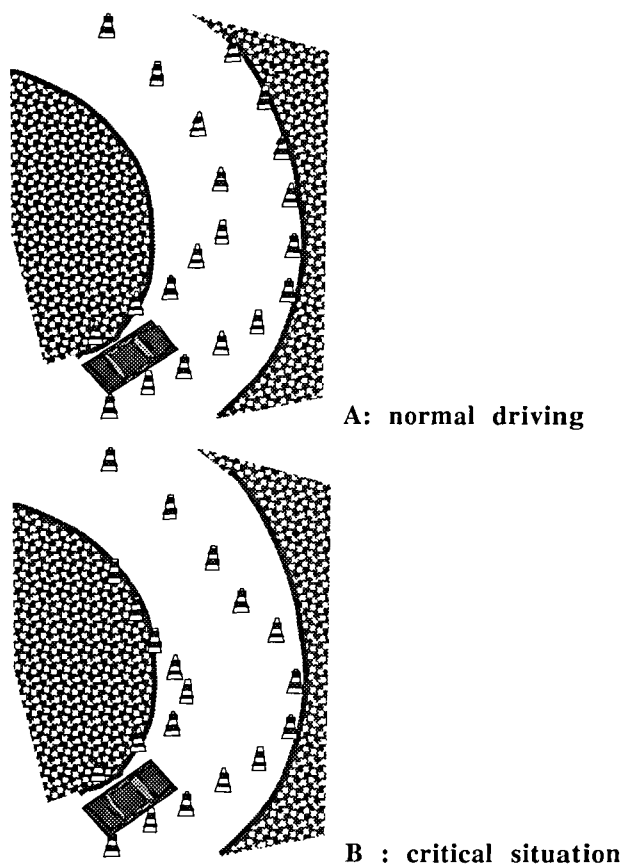
166 average drivers were shared out among three homogeneous groups in terms of age, driving experience and ability to manage stressful situations. Each group had to use a car with specific dynamic characteristics (neutral, oversteer or understeer). The test consisted of three laps of a private track ; the speed being increased for each lap (60 km/h, 70 km/h and 80km/h). The layout of the circuit was modified during the final lap without warning the driver, in order to tighten sharply a curve. This modification, appearing when the car was travelling at a speed of 80 km/h, was to bring about at least a removal of the foot from the accelerator pedal while on a bend.

All the drivers volunteered ; they were working at Renault and none was a professional driver. Their ability to react to a stressful situation has been evaluated within a psychometric test (Stroop test). They did not know the real aim of the study. They only had been told that the way they were driving in a curve will be studied.

They were asked to drive on the right part of the road and to respect the required speed. A professional driver was sitting beside the driver in order to help him to follow the requirements and to ensure safety if the situation became too critical.

Three Renault 19 were used. They were identical except the handling : one was standard, one oversteer and the last one understeer. None of the drivers knew there was several cars and each drove and saw only one car (i.e. 54 drivers for the standard car ; 55 for the oversteer one and 53 for the understeer one).

The track was a winding road. It was marked out with cones to force the drivers to stay on the right part of the road. The critical situation consisted of sharpening one of the bends from a radius of 50 m to 25 m (Figure 1).



**Figure 1. Test site**

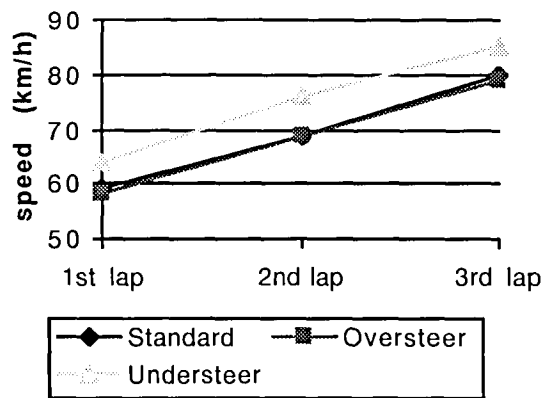
Sensors gave informations about the car dynamic forces and the actions of the driver. Physiological measures were also performed to evaluate his emotional response and his mental load.

### Normal Driving

All the driving before the critical situation was considered as normal driving. Then, it is possible to look at the influence of the type of vehicle (St : standard ; Ov : oversteer ; Ud : understeer) on the observance of the requirements and on the dynamic forces due to the driving signature of the subjects.

The observance of the driving speed for each lap is the first indicator about normal driving (Figure 2) :

- all the drivers easily acceded the required speed,
- understeer car users drove faster (+ 5 km/h) than the others. This difference is statistically significant.



**Figure 2. Respect of the required speed versus the type of car used.**

Longitudinal dynamic forces were rather smooth. Lateral forces were more sizeable but remained in accordance with a normal driving on a trunk road (Table 3). As a mean value has no significance, only the 95 th and 99 th percentile are given (i.e. 95 % of the driving time, the lateral acceleration was below 0.4 g).

**Table 3.**  
**Dynamic forces in normal driving**  
( $\gamma_t$  : lateral acceleration)

	acceleration (g)	deceleration (g)	$\gamma_t$ (g)	yaw speed (°/s)
99th perc.	0.15	- 0.2	0.5	20
95th perc.	0.09	-0.12	0.4	14

These values are similar to previous studies (Lechner, 1993). 95 th percentile is relevant to the limits of comfortable driving where as 99th percentile corresponds to the limits the driver voluntarily reaches.

The three cars can be significantly separated ( $p < 0.05$ ) when considering the lateral forces (Table 4).

**Table 4.**  
**Lateral acceleration and yaw speed versus the type of car during normal driving**  
(St : standard ; Ov : oversteer ; Ud : understeer)

	St	Ov	Ud
99th perc. $\gamma_t$	0.6 g	0.5 g	0.5 g
95th perc. $\gamma_t$	0.5 g	0.4 g	0.4 g
99th perc. yaw speed	24 °/s	18 °/s	18 °/s
95th perc. yaw speed	17 °/s	12 °/s	13 °/s

Significantly higher lateral forces for the standard car may be surprising. It can come from a bias of the study : all the drivers were working for Renault and perhaps they were more used to the feeling of the standard car than to the others. However, the understeer car gave a



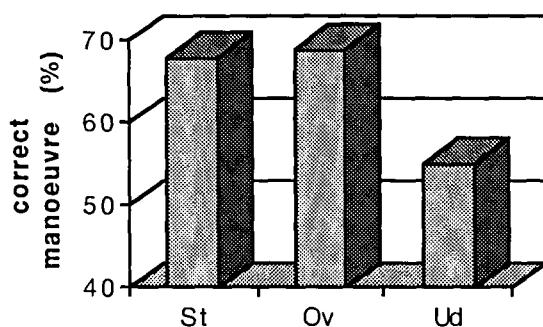
better safety feeling (a better feeling of control ?) than the others, that was testified by the higher driving speed.

### Critical situation

Most of the drivers were really impressed by the sharpening of the curve as the high increase of their heart rate testified even if some of the drivers did not understand what had happened. The physiological response indicates that the driver adapted their steering manoeuvre rather than changing their strategy.

64 % of the drivers were able to pass the sharpended curve without any problem. The mean speed at the entrance of the curve was 74 km/h and the mean slowdown was 19 km/h to reach 55 km/h at the entrance of the narrow curve (Figure 3).

10 % of the drivers negotiated the bend on its external part and they had more difficulties to pass the modified part with a failure ratio of 75 % versus 33 % for those who were driving on the inner part. This observation is linked neither to a particular car nor to the speed.



**Figure 3. Distribution of the drivers who passed the critical curve versus the type of car (St : standard ; Ov : oversteer ; Ud : understeer)**

From this point, the studied population will be separated into two groups : those who passed the curve called "correct" and those who did not called "uncorrect".

Speed is a good criterion to discriminate the quality of the manoeuvre. Wide angle steering was not enough to catch up the correct trajectory. The weak, but significant, differences between the dynamics forces within correct or uncorrect manoeuvres show that the drivers were close to their limits (Table 5).

These values show the importance of the transient event in comparison with the values obtained during normal driving.

**Table 5. Dynamic forces whether the driver passed or not versus the type of car (St : standard ; Ov : oversteer ; Ud : understeer)**

Speed (km/h)	St	Ov	Ud
correct	50	51	51
uncorrect	64	64	62

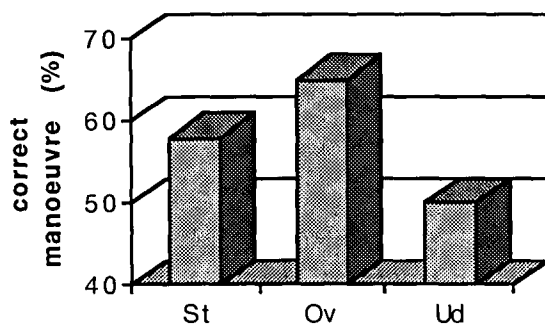
$\gamma_t$ (g)	St	Ov	Ud
correct	0.8	0.8	0.8
uncorrect	1	0.9	0.9

yaw speed (°/s)	St	Ov	Ud
correct	31	32	31
uncorrect	35	37	30

Driving speeds remain homogeneous whatever the car used. They are contained between 31 and 64 km/h

when drivers passed the sharpened curve and between 52 and 74 km/h when they did not. 64 km/h appears to be a limit above none could pass.

If the studied population is restrained to those who passed the curve at speed that overlaps (52 to 64 km/h), all the cars keep almost the same success ratio than for the global population (Figure 4). The size of the group with the understeer car becomes 50 % larger than the other groups : (Standard : N = 24 ; Oversteer : N = 20 ; Understeer : N = 30).



**Figure 4.** Distribution of the drivers who passed the critical curve versus the type of car (52 km/h < driving speed < 64 km/h) (St : standard ; Ov : oversteer ; Ud : understeer)

Referring to the restrained population, the mean speed was 59 km/h for the St and the Ov car and 57 km/h for the Ud car. Lateral dynamic forces became closer between correct and uncorrect manoeuvre but still remained significantly different (Table 6).

**Table 6.**

**Lateral dynamic forces whether the driver passed or not versus the type of car (52 km/h < driving speed < 64 km/h)**

(St : standard ; Ov : oversteer ; Ud : understeer)

$\gamma_t$ (g)	St	Ov	Ud
correct	0.95	0.91	0.92
uncorrect	1	0.9	0.94

yaw speed (°/s)	St	Ov	Ud
correct	32	35	33
uncorrect	35	33	32

Lateral forces were similar for the three cars. The main difference came from the steering manoeuvre required, which was much more important for the Ud car. Inter-vehicles comparisons do not show any difference versus the manoeuvres, however the steering angle was larger when the driver did not pass the sharpened curve. Actually, the time the driver steered is of prime importance. If the car was on the outer part of its lane, or if the driver was surprised, any delay was harmful to the driver especially with the Ud car. The other point is the way the driver held his steering wheel : none of the drivers who were holding their steering wheel with one hand tried to use his second hand, and none succeeded to pass the critical point.

## CONCLUSION

Drivers with the understeer car drove faster than the others (+ 5km/h). At the sharpened point, this difference was not significant any more.

Critical situation induced an increase of 0.4g of lateral acceleration and 14 °/s of yaw speed relatively to the values for comfortable driving.

Paradoxically, if the understeer car gave a better feeling for normal driving, drivers had more difficulties than with the other cars, in the critical situation.

## ACKNOWLEDGMENTS

The authors would like to thanks their colleagues at the Laboratory of Accidentology and Biomechanics (LAB) who kindly give the datas of accidentology.

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## DESIGN AND CONSTRUCTION OF A VARIABLE DYNAMIC VEHICLE

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United States

Paper Number 98-S2-P-27

### ABSTRACT

This paper is a Progress Report describing the design and construction of a "Variable Dynamic Testbed Vehicle", VDTV, suitable for use as a test tool by researchers in the field of automotive safety. The VDTV project was sponsored and funded by the United States Department of Transportation, Intelligent Transportation System/Joint Program Office. The VDTV performance will be programable by way of an Onboard laptop computer readily accessible to the test driver or a test conductor. The vehicle systems available for programming are the vehicle "by wire" systems which are the front and rear steer; steering feel; brakes with ABS, traction control, and yaw control; throttle; front and rear anti-roll bars; and the variable rate suspension. The base vehicle is a Roush Technologies modified 1995 Ford Taurus SHO used in the Bob Bondurant high performance driving school in Phoenix, Arizona. This base vehicle has an experience history of proven performance, low maintenance and high reliability. This base vehicle already contained a roll cage, high performance springs, heavy duty subframe mounts, and a fire control system. Tier one automotive component suppliers provided their latest "ready for production, by wire" components, at essentially their incremental cost for modifying these systems to VDTV requirements for the vehicle systems outlined above. These components were installed on the base vehicle by Roush Technologies. ERIM Automotive was the primary contractor and the Jet Propulsion Laboratory acted as the contract technical manager for the Department of Transportation. The VDTV is designed to be capable of simulating the braking and dynamic performance of a large variety of generic vehicle types ranging from small to large vehicle sizes. A comprehensive onboard data acquisition system is available to record all data from all vehicle sensors. An offboard data processing system will process data into user format. User-supplied equipment can be added to the VDTV by using VDTV supplied power and electronic interface to the

control and measurement subsystem. Vehicle and test condition safety has been provided through the VDTV design and construction process. The VDTV will provide researchers a safe, versatile research tool that can quickly and economically simulate a variety of vehicle test conditions for studying vehicle dynamic performance, human factors, driver physiological performance, and intelligent vehicle crash avoidance systems both singularly or in combination.

### INTRODUCTION

The U. S. Department of Transportation (U. S. DOT), has been conducting crash avoidance research into such vehicle systems as brake performance, vehicle yaw stability, vehicle rollover stability, tire performance, and driver performance for a number of years. Recently, the U. S. DOT has been examining the potential of new high technology crash avoidance system concepts for preventing and/or reducing the severity of crashes in such crash scenarios as rear-end and road departure. Research in these areas often require the testing of many different levels of independent variables. For example, the need to test an array of human factors as a function of different vehicle performance parameters in the past has always required that either the vehicle systems, such as suspension systems, be laboriously changed by hand or that the test equipment be laboriously changed from one test vehicle to another. It was recognized that testing cost could be greatly reduced and testing efficiency could be greatly increased if one could more easily change the test vehicle performance parameters. A feasibility study was conducted to determine if a variable testbed vehicle was technically feasible and what the approximate specifications of such a vehicle might be (1). The study concluded that the design and construction of such a vehicle was technically feasible and that such a testbed vehicle would be extremely valuable for conducting conventional as well as high technology safety research. Based on the favorable results of the above study, a contract entitled, "Variable Dynamic Testbed Vehicle Implementation" was issued by the National

Highway Traffic Safety Administration, United States Department of Transportation, as part of the Intelligent Transportation Initiative, Joint Program Office in September 1996, to design, construct, and test a variable dynamic testbed vehicle.

## METHODOLOGY

The vehicle design part of this study determined that the required vehicle must meet the following two constraints: (1) the vehicle dynamic performance range must be adjustable to cover the production vehicle range from low performance to high performance for crash avoidance research and, (2) the vehicle must look and feel like a production vehicle environment for human factors research. A VDTV requirements document (2) was created which spelled out in detail what the safety, functional, and quality assurance requirements the delivered VDTV must meet. The VDTV will be required to pass a "performance verification test", (PVT) at the beginning and end of a test sequence to demonstrate that the vehicle meets all of the design requirements with respect to safety and function.

## SAFETY

The VDTV system, which includes drivers, roads, maneuvers, and operational experience as well as the vehicle itself, shall provide the level of safety expected to be equivalent to that experienced in normal passenger car operation throughout the US. The VDTV will be used on approved test track roads and surfaces, not on public roads. Approved roads will have safe run-off areas or barriers which significantly reduce the probability of a severe impact in case of a failure. Occupant safety was given primary consideration. The vehicle has a four-point harness available for the driver and system manager, a full roll cage, and a halon fire control system in the occupant compartment, trunk, and engine compartment.

Analysis performed early in the vehicle design program demonstrated that the VDTV is secure from rollover on a flat surface under the following most severe conditions:

- (1) Vehicle configuration with the highest performance tires used during any part of the "Acceptance Test" on a dry high friction surface.
- (2) Operation on a large, flat, paved surface including:
  - (a) Any combined turn and brake maneuver, both at limit performance.
  - (b) The J turn and the obstacle avoidance maneuver of the PVT.

## PROJECT CONSORTIUM

The base vehicle displaying the most requirements calculated to be necessary for a viable VDTV was found to be a Roush Technologies prepared 1995 Ford Taurus SHO used in the Bob Bondurant school of high performance driving. This base vehicle has an experience history of proven high performance, low maintainability, and high safety and reliability. This vehicle already contained a roll cage, high performance springs, heavy duty subframe mounts, and a fire control system. This vehicle satisfied several of the high priority requirements which are: high availability for testing, low maintenance downtime for maximum availability and low maintenance cost, proven durability during high stress high acceleration testing, built in safety items such as a proven roll bar cage, four point safety harness and a halon fire control system in the vehicle engine compartment, passenger compartment, and vehicle trunk.

Tier one automotive component suppliers supplied near production or "ready for production, by wire" components for installation on the base vehicle. The VDTV program participants are the following:

- (1) U. S. DOT/ National Highway Traffic Safety Administration/Federal Highway Administration Joint Program Office
- (2) Jet Propulsion Laboratory - Technical Manager and Measurement Subsystem
- (3) ERIM Automotive - VDTV System Contractor, Hardware Integrator and Software Developer

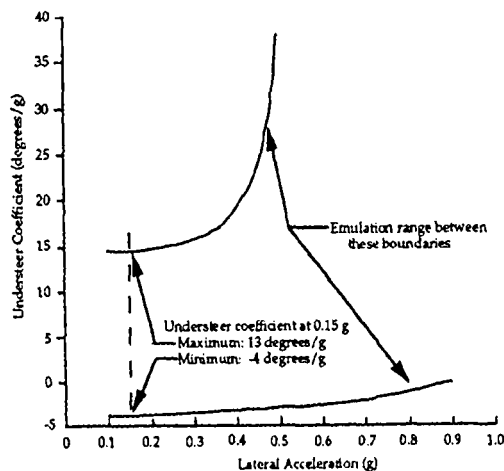
- (4) Roush Technologies - Vehicle Design, Integration, Construction, and Test Support
- (5) GM - Delphi - Brake-by-wire (ABS, Traction Control & Yaw control), Variable Shock Absorber, and Variable Anti-Roll Bar
- (6) TRW - Steer-by-Wire (Front and Rear) and Steering Feel
- (7) Bosch - Throttle-by-Wire
- (8) Goodyear - High Performance Tires
- (9) Milliken Research Associates - Dynamic Modeling Analysis & Control Algorithms

## VEHICLE PERFORMANCE REQUIREMENTS

The VDTV dynamic performance was designed to be controllable throughout its entire range via commands from a laptop computer using a single vehicle mechanical configuration. The following examples demonstrate various important vehicle performance measures and levels the VDTV has been designed to achieve:

### Understeer Coefficient

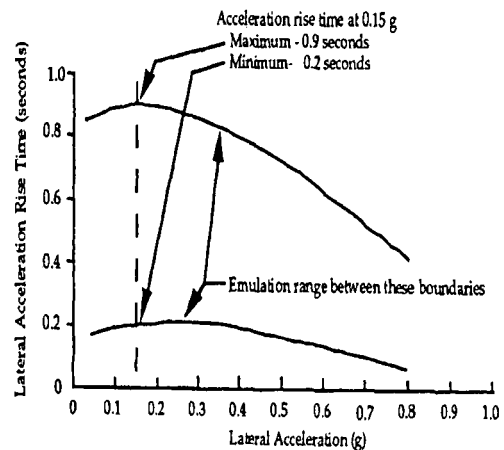
The understeer coefficient simulation range is shown in Figure 1. The understeer coefficient range is plotted as a function of lateral acceleration. The possible VDTV understeer simulation range at 0.15G lateral acceleration is shown to be from plus 13 degrees/G down to minus 4 degrees/G.



**Figure 1.** Understeer Coefficient Emulation.

### 90% Lateral Acceleration Rise Time

The 90% rise time range for the VDTV lateral acceleration resulting from a "step steer" input J turn type maneuver is plotted in Figure 2. At a specified level of lateral acceleration, the VDTV shall be programmable to achieve a 90% acceleration rise time that falls between the upper and lower bounds depicted in Figure 2. The 90% acceleration rise time as a function of lateral acceleration.



**Figure 2.** Lateral Acceleration rise time versus Lateral Acceleration.

### Steady State Lateral Acceleration

The VDTV is designed to attain a steady state lateral acceleration of at least 0.95G under the following conditions:

- i. A 30 meter diameter circle.
- ii Production type tires and normal road surfaces. (P279/40 ZR-17 GSC)

The VDTV can attain higher lateral accelerations when equipped with the same size S-compound racing tires.

### Longitudinal Acceleration

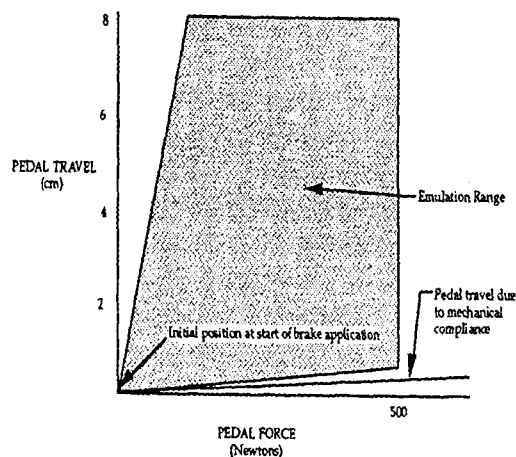
The VDTV is designed to accelerate from 0 to 100 km/h in less than 9 seconds, with a starting condition of the engine idling. The VDTV is designed to accelerate from 70 to 105 km/h in less than 5.5 seconds.

### Longitudinal Deceleration

The VDTV is designed to decelerate from 100 km/h to 0 in less than 40 meters and from 130 km/h to 0 in less than 70 meters. The VDTV is also designed to do 10 successive 0.5G stops from 100 km/h with an increase in pedal force from the first stop to the tenth stop not greater than 50% of the first stop under conditions of full acceleration between stops. The brake-by-wire system is designed to be capable of locking all four wheels at a speed of 160 km/h. The VDTV brake feel system will provide mechanically variable pedal travel/force characteristics within the simulation range shown in Figure 3.

The VDTV will be equipped with the latest ABS, traction control, and yaw control systems with on/off capability and multiple control algorithms available which are programmable from a laptop computer.

The VDTV is designed to have very fine longitudinal speed control to investigate possible platooning boundaries, as well as to study intelligent cruise control and crash avoidance systems.

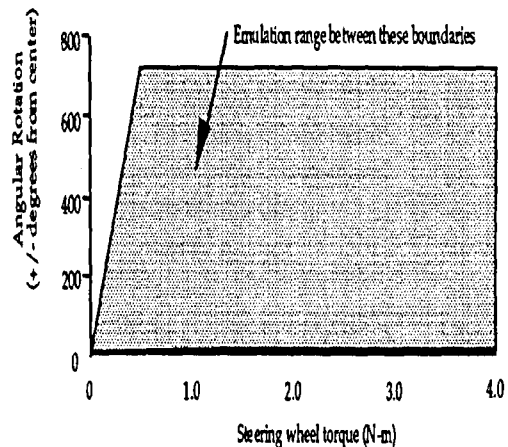


**Figure 3.** Brake Feel Emulation Range

### Steering Wheel Feel

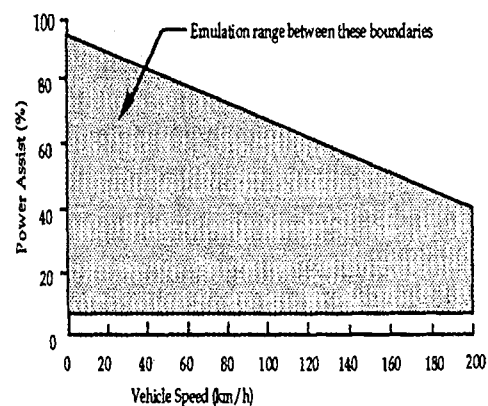
Steering wheel feel is an important parameter for human factors research. Since the by-wire implementation of the front wheel steering disconnects all energy normally transmitted via mechanical connections from the road/tire interface to the steering wheel, the steering feel subsystem

must simulate the basic force characteristics of a representative vehicle such as self-aligning torque from mechanical and pneumatic trail. The steering system torque/rotation simulation is designed to include the range shown in Figure 4.



**Figure 4.** Steering Wheel Torque/Angular Rotation Emulation.

The steering ratio variability in terms of steering wheel angle/front wheel angle is variable via laptop computer commands in a range from the full torque/no angular rotation mode to 20:1. The steering power assist shall be variable within the simulation range shown in Figure 5.



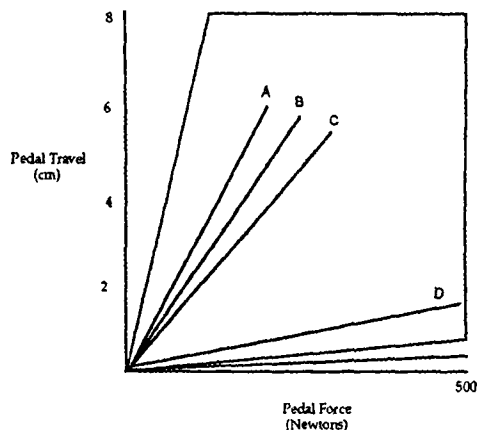
**Figure 5.** Power Assist Emulation Range.

The laptop computer commands provide a selection of different power assist algorithms.

The steering system also has the capability to program in, via laptop computer, vibration, friction, and haptic inputs.

### Throttle-by-wire

The VDTV throttle control system has two different operational modes: (1) typical operation during research activities, and (2) fine power control for longitudinal distance keeping. Throttle feel characteristics are changed by changeable springs with a range as shown in Figure 6.



**Figure 6.** Throttle Pedal Feel..

### Rear Wheel Steer-by-wire

Rear wheel steer is used to enhance the fidelity of small car emulation. The rear wheel steer system is designed to have a rotation capability of  $\pm 2$  degrees with a -3 dB bandwidth of 15 Hz. The rear wheel steer system includes the capability to deactivate for front wheel steer only or control the rear steering angle according to algorithms selected via laptop computer commands.

### Semi-Active Suspension

The VDTV has semi-active suspension dampers controllable from the laptop computer. The damping rates for all four wheels have the capability of being

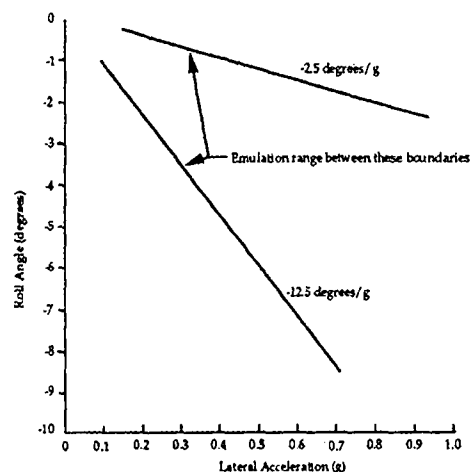
automatically changed on an individual basis under the control of algorithms and/or preset. At least three levels of damping forces were to be provided by the semi-active suspension:

At a piston speed of 75 cm/sec, the “hardest” damping forces were to be at least 3400 and 900 Newtons in extension and compression, respectively.

- (1) At a piston speed of 75 cm/sec, the “softest” damping forces were to be at least 1200 and 670 Newtons in extension and compression, respectively.
- (2) At a piston speed of 75 cm/sec, the third damping force was to be approximately midway between the hardest and softest forces.

### Front and Rear Active Anti-Roll Bar System

The VDTV is fitted with front and rear active anti-roll bar systems that are programmable from a laptop computer. Variable rate front and rear anti-roll bars are important in changing the total roll stiffness and/or the front to rear load transfer distribution and limit understeer of the VDTV. Consequently, these actively controlled systems will greatly facilitate human factor investigations and dynamic maneuver investigations. The required simulation range of the VDTV active anti-roll bar controlled system is shown in Figure 7.



**Figure 7.** Emulation Range of an Active Anti-Roll Controlled System.



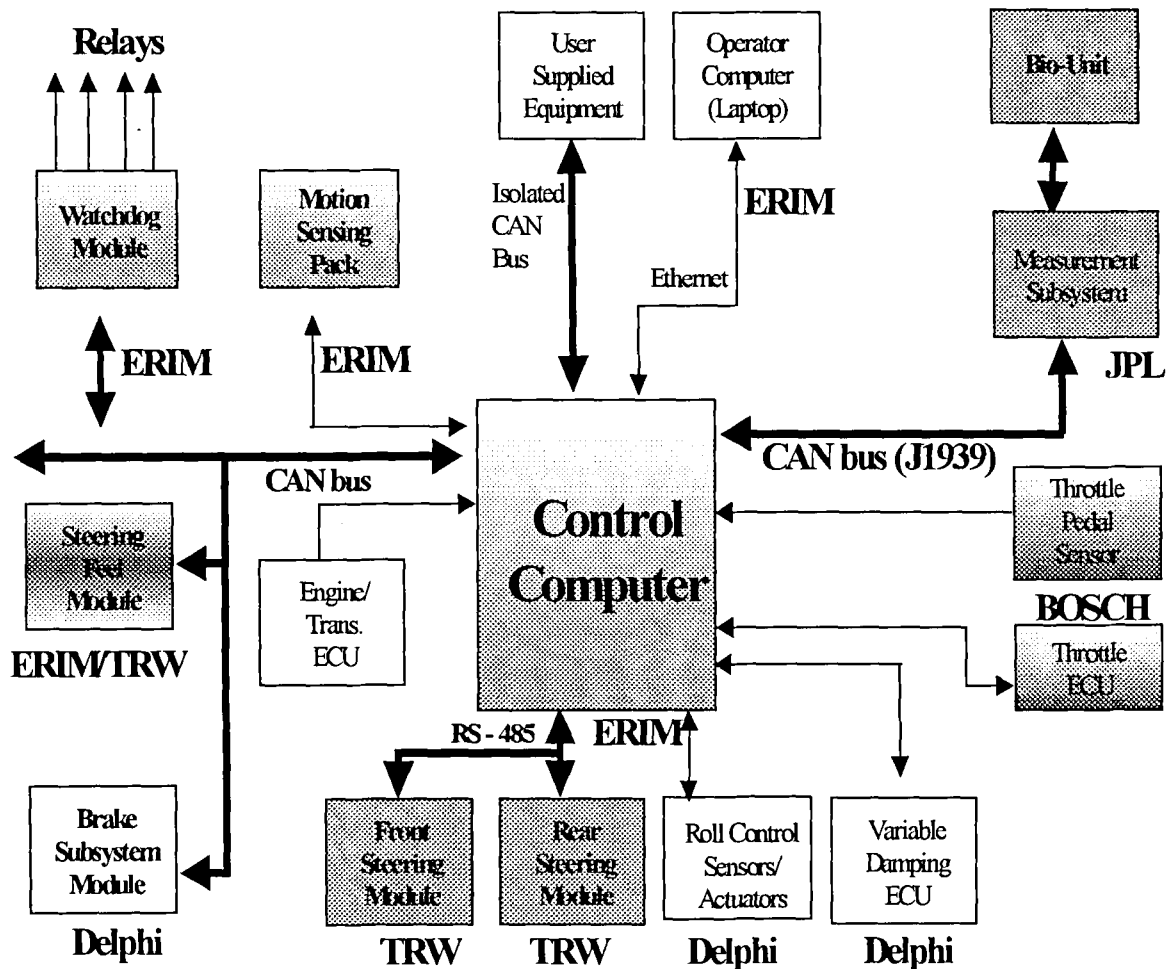
The Steering feel system uses an electric motor to provide force-feedback to the handwheel.

## VEHICLE DESIGN AND CONSTRUCTION

The VDTV could only meet the above performance requirements by having vehicle systems that are variable in performance and easily changed through active control by way of a laptop computer or a similar device. This requirement was designed to be attained by having control-by-wire vehicle systems. These control-by-wire type systems were not readily available and would have been very expensive and time consuming to develop from scratch. However, that proved to be unnecessary. The VDTV major contractor, ERIM Automotive International, was able to put together a consortium of tier one automotive component suppliers who offered their latest "ready for production, off-the-shelf", "drive-by-wire" systems and components. The diagram in Figure 8 gives an overview of the VDTV by-wire systems, the major suppliers, and the general electronic relationships among these systems. The cooperation of the automotive industry greatly enhanced the affordability and relevancy of the VDTV to present and future technology.

A brief explanation of the elements contained in Figure 8 are presented in the following comments:

- i. Control Computer - this hardware supplied by dSpace. Acts as the vehicle-level Control computer and coordinates the activities of all of the other subsystems. Emulation and control strategies are implemented on this computer.
- ii. Operator Computer - Laptop computer interfaced to the control computer via an Ethernet link. This computer is used for data display and operator input.
- iii. Measurement Subsystem - Acts as the data storage device for the VDTV and records all of telemetry from the Control Computer. This Pentium PC computer also interfaces to the Bio-unit for measuring physiological data. Digital video will also be recorded by this subsystem.
- iv. Throttle Unit - This by-wire subsystem replaces the mechanical throttle linkage.
- v. Steering System - The front and rear steering racks are electrically driven and electronically controlled. They are interfaced to the steering wheel by a mechanical linkage as a back-up mechanism. Normally, the steering wheel is mechanically isolated from the steering system. The steering feel system uses an electric motor to provide force-feedback to the handwheel.
- vi. Brake System - This system is electrically controlled with hydraulic back-up. The systems includes four wheel ABS, traction control, and yaw control. Autonomous braking is engaged via the control computer.
- vii. Motion Sensing Pack - This unit serves as an inertial measurement unit for the VDTV. Utilizing micro-machined accelerometers and fiber-optic gyros, this unit measures body-frame and earth-frame accelerations and rotations.
- viii. Watchdog Module - Oversees the activities of the control computer and engages back-up systems when failures are detected.
- ix. Roll Control System - Provides for active control of body roll via electrically-controlled hydraulic pistons in the stabilizer bar connection to the vehicle struts. Front and rear stabilizer stiffness is independently controllable for maximum flexibility.
- x. Damping System - Continuously variable real-time damping system provides the capability to vary the ride characteristics of the vehicle so as to explore their influence on emergency driving performance.
- xi. User-Supplied Equipment - Subsystem for future testing on the vehicle. Examples include intelligent cruise control, collision warning, lane following, and other such systems.



**Figure 8.** VDTV Electronics.

The above control systems are being installed on a modified 1995 Ford Taurus SHO. The SHO was modified by Roush Technologies based on experience gained in modifying previous SHO vehicles for the Bob Bondurant school of high performance driving. This vehicle already contained a full roll cage, high performance springs, heavy duty subframe mounts, and a fire control system. This base vehicle has an experience history of proven high performance, low maintainability and high reliability.

A new approach for developing the VDTV control software was used to greatly reduce the amount of handwritten software development on the VDTV program, and to ease the modification of the VDTV to support a variety of research needs. The graphical programming tool SIMULINK from the Mathworks, Inc., was utilized to diagram the control system. A

special compiler was then used to convert this graphical description into C code (and ultimately machine code) compatible with the in-vehicle computer supplied by dSpace, Inc. This in-vehicle computer utilizes a TI 320C40 DSP and a DEC Alpha RISC processor to control and monitor the vehicle in real time.

The graphical control diagrams developed in SIMULINK are also integrated with a 17-DOF dynamics model of the VDTV for off-line simulation of control strategies and algorithms before implementation on the vehicle.

Milliken Research Associates (MRA) converted the Systems Technology, Inc., (STI) model developed for DOT in 1992 into the SIMULINK environment to serve as the basis of the VDTV model. MRA modified and extended the model to accommodate

the unique features of the VDTV. MRA also performed a series of simulations (using their own models and software) to evaluate the capabilities to vary the dynamics of the vehicle in real-time. This capability in real-time is the cornerstone of the vehicle's ability to simulate different classes of vehicles and to vary the dynamic properties individually. The MRA simulation work led to the control algorithms being used in the VDTV.

The following is a brief description of the VDTV "by-wire" control systems chosen for incorporation into the VDTV.

### Front and Rear Steering Racks

The front and rear steering racks were supplied by TRW. They are driven by an electric motor from electronic signals coming from either the steering wheel or the algorithm computer. The front steering rack is mechanically connected to the steering wheel through a clutch which is always disengaged except during a system failure. The rear steering rack is also driven by an electric motor from electronic signals coming from the algorithm computer. The fail-safe position of the rear steering rack has not yet been determined. There are basically two choices at the present time, either return to zero steer angle or freeze the steering angle at the point of failure. However, safety algorithms can be constructed to handle different situations. The VDTV steering subsystem is diagramed in Figure 9.

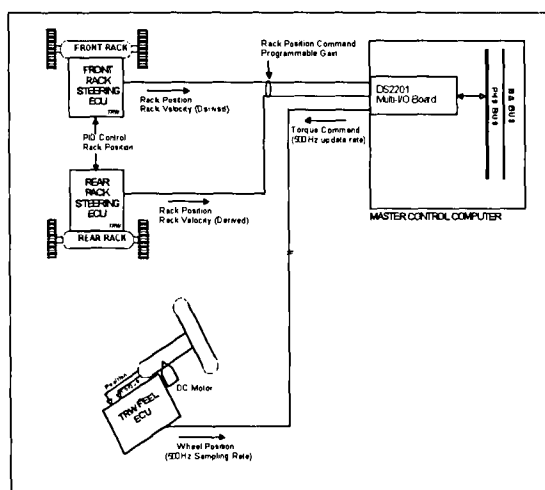


Figure 9. Steering Subsystem.

The steering racks have programmable gains and inputs controlled by the laptop computer. They also have a programmable steering feel capability.

### Brake System

The VDTV is being equipped with an advanced brake-by-wire system supplied by GM-Delphi that is production ready. The front brake caliper has been upgraded from a 10 inch diameter one to a 12 inch one to enhance the braking capability of the vehicle. The braking system is an advanced four-wheel ABS system with traction control and a four-wheel yaw control system. All of these systems will have on-and-off switches for ease of testing. The VDTV brake and brake feel subsystem is shown in Figure 10.

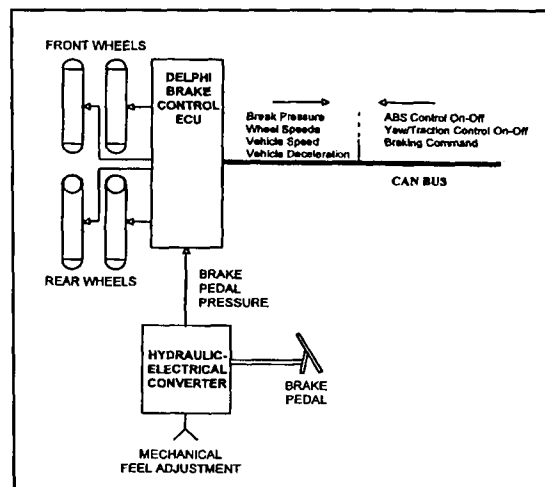
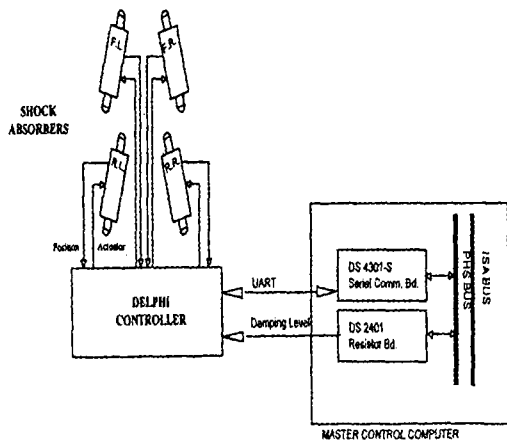


Figure 10. Braking System.

### Variable Rate Suspension System

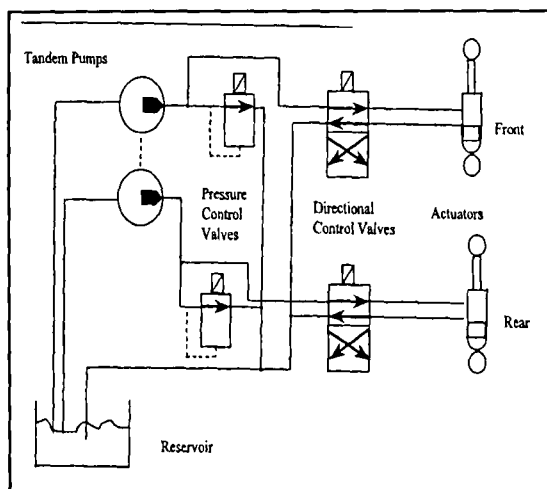
The VDTV is being equipped with a variable rate suspension system produced and supplied by GM-Delphi. The system is programmable from the laptop computer and will provide a wide variety of suspension stiffness for performing human factors and vehicle dynamics research. The system is shown in Figure 11.



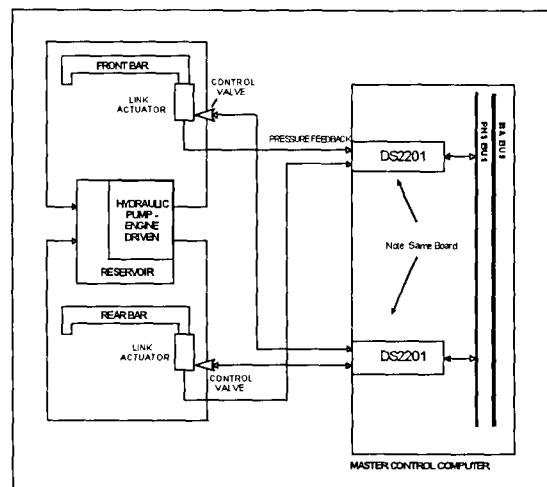
**Figure 11.** Damper Subsystem.

#### Front and Rear Anti-Roll Bars

The VDTV is being equipped with fully adjustable front and rear anti-roll bars supplied by GM-Delphi which can be controlled by the laptop computer. The bars can be readily changed to provide more or less roll stiffness. This capability will allow the research to vary the total vehicle roll stiffness, as well as the percentage front-to-rear stiffness distribution. The variable front-to-rear stiffness distribution capability will greatly enhance the ability of researchers to control and change the VDTV understeer coefficient. The active roll control system is shown in Figures 12 and 13.



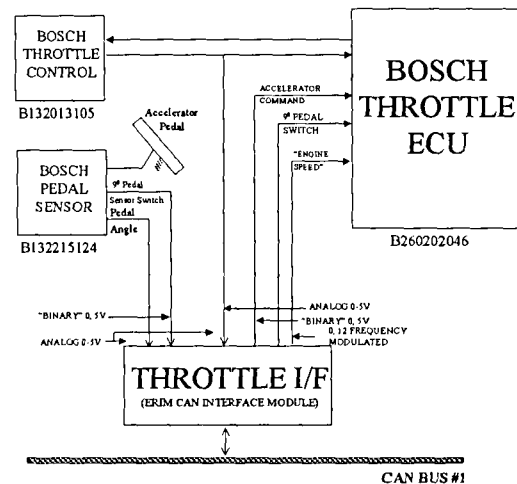
**Figure 12.** Active Roll Control.



**Figure 13.** Roll Control System.

#### Throttle-by-wire System

The VDTV is being equipped with a throttle-by-wire system supplied by Bosch. The system will be completely programmable from the laptop computer. The throttle feel system will be a set of changeable springs. The VDTV throttle-by-wire system is shown in Figure 14.



**Figure 14.** Throttle-By-Wire Subsystem.

#### PROGRAM RESULTS

The VDTV is scheduled to begin shakedown tests at the Vehicle Research and Test Center in Ohio on June 8, 1998. The control systems, safety systems, and data measurement systems will all be thoroughly checked out before a series of VDTV acceptance

tests are begun. The vehicle has been designed to meet certain specifications for performance and safety. After the VDTV has passed the acceptance tests, it will be used as a test tool in planned research programs.

## REFERENCES

**Marriott, A.T.**, *"Variable Dynamic Testbed Vehicle Study"*, Department of Transportation Contract Technical Report Numbers DOT HS 808 178, (Volume I) Technical Summary; DOT HS 808 179, (Volume II) Technical Results; DOT HS 808 180 (Volume III) Appendixes

**VDTV Contract Document** entitled *"Exhibit I - Variable Dynamic Testbed Vehicle Functional Requirements"*

# A HEAVY VEHICLE DROWSY DRIVER DETECTION AND WARNING SYSTEM: SCIENTIFIC ISSUES AND TECHNICAL CHALLENGES

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Paper Number 98-S2-P-30

## ABSTRACT

Even though loss of alertness has been detected in laboratory driving simulators with impressive accuracy, there are numerous scientific issues and technical challenges associated with developing a field-operational drowsiness detection and warning system. The key *scientific issues* are related to the development of fieldable detection models and warning systems. Issues include model validation, individualized versus generalized monitoring, and detection and warning versus activity-based maintenance. The key *technical challenges* are related to system operability and acceptance. Challenges include system upkeep and calibration, driver and vehicle compatibility, risk compensation and migration, alertness restoration, and operational reliability. This paper provides an overview of the drowsy driver problem in the United States, a description of NHTSA's drowsy driver technology program, and an introduction to some of the scientific issues and technical challenges that confront system deployment.

## INTRODUCTION

Research is underway at the U.S. National Highway Traffic Safety Administration to develop, test, and evaluate a prototype drowsy driver detection and warning system for commercial vehicle drivers (1996-1998). Even though the loss of alertness in drivers has been detected in laboratory driving simulators with impressive accuracy (Wierwille et al, 1996), there remain numerous scientific issues and technical challenges associated with field deployment. This paper provides an overview of the drowsy driver problem in the United States, a description of NHTSA's drowsy driver technology program, and an introduction to some of the scientific issues and technical challenges that confront system deployment.

The *scientific issues* discussed are related to the development of detection models and warning systems. The discussion includes the issues of model validation, individualized versus generalized monitoring, and detection and warning versus activity-based maintenance. *Technical challenges* relate to system operability and acceptance,

including system upkeep and calibration, driver and vehicle compatibility, risk compensation and migration, alertness restoration, and operational reliability.

While the list of issues and challenges is not exhaustive, it provides an initial framework suggestive of deployment alternatives as the detection and warning system is developed. The prototype development team is presently charged to fully understand these concerns, and to complete the initial prototype by the end of fiscal year 1998. Ultimately, the final system seeks to reduce the annual numbers of injuries and deaths associated with drowsiness.

## Problem Size

Currently, our understanding of the drowsy driver problem in the United States is based on NHTSA's revised estimates for the 5-year period between 1989 and 1993 (Knippling et al, 1995). An average annual total of 6.3 million police reported crashes occurred during this period. Of these, approximately 100,000 crashes per year (1.6% of 6.3 million) were identified on Police Crash Reports (PCR) where drowsiness was indicated, and from a review of "Drift-Out-Of-Lane" crashes not specifically indicated but which had drowsiness characteristics. Approximately 71,000 of all drowsy-related crashes involved non-fatal injuries, whereas 1,357 drowsy-related fatal crashes resulted in 1,544 fatalities (3.6% of all fatal crashes), as reported by the Fatality Analysis Reporting System (FARS). Nevertheless, many run-off-roadway crashes are not reported or can not be verified by police, suggesting that the problem is much larger than previously estimated.

Regarding differences between cars and trucks, approximately 96% of annual drowsy driver crashes (96,000 total including 1,429 fatalities) involved drivers of passenger vehicles, whereas only 3.3% (3,300 total including 84 fatalities) involved drivers of combination-unit trucks. Nevertheless, drowsiness was cited in more truck crash involvements (.82%) than passenger vehicle crashes (.52%). In addition, the risk of a drowsiness-related crash in a combination-unit truck's operational life is 4.5 times greater than that of passenger vehicles, because of greater exposure (60K versus 11K miles/year), longer operational life (15 versus 13 years), and more night driving (Knippling & Wang, 1994). There is also a greater likelihood of injury in heavy vehicle crashes. Approximately 37% of the truck-related drowsy driver fatalities and 20% of the non-fatal injuries occurred to individuals outside the truck, compared to 12% of the

fatalities and 13% of the non-fatal injuries from drowsy passenger vehicle drivers.

### **Drowsy Driver Technology Program**

The objective of NHTSA's Drowsy Driver Technology Program is to develop, test, and evaluate a prototype drowsy driver detection and warning system for commercial motor vehicle drivers. The program began in fiscal year 1996 and is scheduled to continue through fiscal year 1998. One of the key tasks of the program is to develop drowsiness detection models and algorithms based on field data. However, laboratory-based experiments will also be conducted to suggest sensors and algorithms for further validation in the context of over-the-road driving. There are a variety of university, industry, and government partners associated with the laboratory and field study elements of the program.

First, in partnership with the University of Pennsylvania (funded by the Federal Highway Administration's Office of Motor Carriers), candidate sensors are being validated by monitoring sleep deprived subjects in a controlled laboratory setting. Subjects undergo vigilance and cognitive tests while deprived of sleep. Specifically, polysomnographic and performance measures are collected continuously; subjects are either "alerted" or "not-alerted" about their drowsiness as they become drowsy over a 20 hour period. Alerted and unalerted conditions are experimentally comparable because the presence or absence of an alerting stimuli could alter the response characteristic of certain devices. As another part of the validation process, "blind" data from the experiments are provided to the vendors of each device to determine when the drowsiness episodes occurred (prospective phase). Successful device vendors from the prospective phase receive algorithms from each of the other device vendors, as an opportunity to improve the detectability of their respective methods (retrospective phase).

Second, NHTSA's principal industry partner for building the prototype system is Carnegie Mellon Research Institute (CMRI), in Pittsburgh, Pennsylvania. CMRI is the technical lead on the project and has outfitted several commercial trucks (courtesy of Pitt-Ohio Express, Inc.) with numerous sensors and an automated data collection system. Field studies are designed to unobtrusively monitor commercial truck drivers over 10 hour overnight express runs. In the procedure, numerous performance and behavioral measures are collected as the foundation for developing detection models. This field work is guided by drowsiness detection procedures, which were developed under NHTSA sponsorship over a five year period, based

on driving studies in simulators (Wierwille et al, 1996). However, a number of new detection model and algorithm approaches are also being developed and tested from the new field data, including the measures from sensors validated in the laboratory phase.

Finally, another government agency partner is the Naval Health Research Center (NHRC) in San Diego, California. NHRC provides special expertise in monitoring drowsiness from a recently developed method of processing electroencephalograph (EEG) signals. NHRC's role on the team is to assist in the development of field-based drowsiness detection models, and to provide a psychophysiological index of drowsiness previously developed under contract with the Office of Naval Research. The validity of the NHRC drowsiness detection metric will also be examined under the prospective and retrospective phases of the laboratory study.

### **SCIENTIFIC ISSUES - DETECTION MODELS AND WARNING SYSTEMS**

#### **Model Validation**

Model validation is the principal activity of the program. These models derive their ability to detect changes in alertness from relationships among factors, the correlations between which are built up from data collected during observed levels of alertness. As a result, models represent relationships among the conditions required for drowsiness to be detected. For example, conditions may include drifting out of lane, excessive lane deviations, drift and jerk steering, percentage of eye closure, etc. Thus, a model might specify that a certain magnitude of deviation within a lane can be expected from a certain percentage of eye closure. In addition to prediction, models also specify the relative importance of relationships among the measures such that we might also gain an improved understanding of the important behavioral and performance components of driving.

**Performance and Physiology** - As the program goal is to develop a prototype system, one of our most important considerations is implementation. For example, we do not expect that commercial drivers will accept a system that requires a driver to don a cap wired with electrodes. Nevertheless, a model could be based on a measure like EEG if shown to be valid. Such a "gold" standard or yardstick by which drowsiness can be measured is important for building models that relate specific changes in physiology to driving performance. Thus, one option is

to detect drowsiness based on performance inputs alone, once a strong relationship between driving performance and physiology has been established.

Another modeling option is to base the detection on a valid psychophysical index alone, if it could be measured unobtrusively. Specifically, ocular movement will soon be measured unobtrusively from within the vehicle (a 1998 NHTSA Small Business Innovative Research program initiative). This capability might provide direct access to an ocular index of drowsiness. Thus, the validation of an ocular index of drowsiness might result in: 1) models that relate driving performance to ocular measures, 2) models that relate ocular measures to other previously validated psychophysical indices of drowsiness, and/or 3) models that relate driving performance to ocular and/or other valid indices.

**Normative Weighting and Event-Driven Models** - It is possible that quantitative models alone can *not* be produced from the measures obtained in the field study. Therefore, it is an option to explore improving the quantitative models with various qualitative data related to normative trends in drowsy driving. For example, according to data from NHTSA's General Estimates System (GES), police reported drowsy related crashes occur most frequently between 1:00 a.m. and 5:00 a.m., and again in late afternoon between 3:00 p.m. and 6:00 p.m. Information is also available regarding the number of drowsy related crashes, based on the number of hours driven. Therefore, in a normatively-weighted model, a qualitative rule could be used to mediate the alarm/warning threshold of a data-driven model according to population trends.

Similarly, model validity might also be improved using knowledge about events that occur during the particular time-line of travel. For example, information about the frequency of stops, the duration of stops, regularity of speed, number of passengers, changes in air flow and temperature, and noise levels, could be measured and used to modify the detection capability of the model. Such an algorithm would detect departures from previously determined normative levels. For example, the alarm/warning threshold of a detection system could be lowered when there is an absence of an environmental change; a monotonous environment might indicate a pre-condition for drowsiness. Therefore, the validity of a quantitative detection model might be improved using qualitative information about the population of drivers and/or about the experience of a particular driver. It is also possible that the most useful detection model might be based on the qualitative information alone.

In sum, there are numerous modeling opportunities, all of which offer promise in producing an operational system. As a result, the prototype system could be based on some combination of driving performance, ocular behavior, and/or the inclusion of normative and event based heuristics.

### **Individualized vs Generalized Models**

Individualized versus generalized models are distinguished as those which either detect loss of alertness in a single driver or among all drivers, respectively. The issue is that quantitative models utilize the response data from only a small sample of drivers. Therefore, predictions about a larger population of drivers must be derived statistically. Nevertheless, any large differences among individual drivers could overwhelm any otherwise significant effect related to the group. It is, therefore, likely that a detection model could be improved by using specific knowledge about an individual driver. Moreover, individualized models could include normative or event information, as previously described. Lastly, some technologies have been shown to detect an individual drowsy "signature". For example, certain classes of neural networks can learn baseline driver behavior, and then warn the driver regarding departures from normal "alert" patterns. Both group-based and individualized models are potential outcomes of the research.

### **Detection and Warning vs Activity-Based Maintenance**

Detection and warning versus activity-based maintenance is an issue that contrasts the detection modeling approach of our program, with an "activity-based" approach that requires continuous driver interaction. For example, there are several devices that could alert the driver when a specific behavior fails. One device sounds an alarm when any change in steering wheel motion stops. Presumably, moments of motionless steering may indicate that the driver has fallen asleep. However, there are numerous differences in driving style and roadway conditions that result in motionless steering. Thus, when avoiding frequent alarms during normal periods of motionless steering, steering could become erratic and unsafe.

Another device measures a driver's reaction time to a small light, which is illuminated following a *random* elapsed period of time. A button must be pressed within 3 seconds after the small light is illuminated or else a buzzer sounds. This secondary task forces the driver to monitor a specific location inside the vehicle for the random



occurrence of a single light. Monitoring a random event, not related to vehicle operation, could dangerously divide attention away from the roadway and mirrors. Still another device comprises two alarms; one, if a button is not pressed before an *adjustable* time interval, and two, if a second button is not pressed within another adjustable time period following the occurrence of the first alarm.

There are many compromises to driver safety in using activity-based alertness maintenance devices. Nevertheless, some form of activity-based device, which does not interfere with safe driving, might provide a useful countermeasure to drowsiness. Perhaps a future system might offer some combination of passive detection and alarm/warning methods, with an activity-based system.

## **TECHNICAL CHALLENGES - OPERABILITY & ACCEPTANCE**

### **System Upkeep & Calibration**

System upkeep and calibration is perhaps the most important technical challenge in designing a generally useful system. The system must be easy to learn, easy to use, and easy to maintain. However, certain sensors might be more difficult for passenger vehicle owners to maintain and calibrate on a regular basis. For commercial carriers, upkeep and calibration might be achieved during regular periods of maintenance.

The difficulty of this challenge depends on which sensors are required to support a valid detection model. For example, a camera-based lanekeeping system might require regular lens cleaning and alignment checking. Thus, for a non-technically oriented consumer, the system might also require a performance monitoring and fault localization (PMFL) device to automatically inform drivers if their system performance degrades. Our challenge, then, is that regardless of how valid and reliable in detecting drowsiness, the fielded system must be easily maintained and calibrated.

### **Driver-Vehicle Compatibility**

Driver-vehicle compatibility is presented not so much as a challenge of system design, but as an activity for building engineering models of driver-vehicle interaction. There exist various guidelines on vehicle *interfaces*, but there are no known models that specifically address driver-vehicle *interaction*. Such models would constitute computational methods for predicting human performance in vehicles. As a start, cognitive models of driver-vehicle interaction could arise from, as well as contribute to the existing wealth of

knowledge from cognitive science and cognitive psychology. The challenge is to focus that knowledge as an organized framework of methods, whereby quantitative models of driver/vehicle interaction may be developed. Other specialty areas in human factors have previously begun this process. For example, in the area of user-computer interaction, there exist a number of models, which characterize the interaction (not necessarily the interface) between users and computer systems. Many of the basic components of previous models of human-machine dialog could also be applied to develop predictive models of driver-vehicle interaction. The present research contributes to this knowledge base, specifically with regard to the models developed that specify relationships between physiology and performance.

### **Risk Compensation & Migration**

Risk compensation and migration relate to diminished operational effectiveness due to the misuse of a countermeasure by drivers, as well as external sources of probability not associated with the detectability of a device. First, risk compensation refers to the undesired use of a countermeasure that reduces a driver's awareness of the actual risks associated with certain risky driving behaviors. For example, depending on how the system reports loss of alertness, drivers may use the information to continue driving. It is well known that drivers are often motivated to keep driving, even under impaired levels of drowsiness. Drivers will persist in driving drowsy for many reasons including proximity to their destination, safety concerns about sleeping at rest areas, lodging alternatives, and delays in schedule, etc. The technical challenge is to minimize risk compensation through the design of the user interface. For example, a continuous "fuel gauge" display of alertness might encourage drivers to continue driving, whereas a single threshold alarm would communicate that falling asleep at the wheel is imminent.

Second, risk migration refers to externally determined probabilities, which can affect the overall performance of the system. For example, there have been informal reports suggesting that with roadside rumble strips, there are fewer run-off-road crashes for those road segments that contain rumble strips. However, overall, the same number of crashes occur on that particular highway. It is as though the incidences "migrate" to subsequent road segments without the rumble strips. There are no models to predict this phenomenon, but it suggests that there are other probabilities involved that could influence the effectiveness of the system. Therefore, part of the challenge is confronting problems that are unexpected.

## A COLLISION WARNING ALGORITHM FOR REAR-END COLLISIONS

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### ABSTRACT

The purpose of this paper is to develop an experimentally-based rear end collision warning algorithm for the situation where two vehicles are initially traveling at the same speed in the same direction when the lead vehicle begins to brake. The full variety of initial conditions of vehicular motion are analyzed to determine the proper collision warning algorithm. The analysis shows that knowledge of traveling speed, headway, and lead-vehicle deceleration is sufficient to determine the type of relative motion. This can be coupled with warning logic and principles of vehicle dynamics to produce warning algorithms. An approach to warning implementation is suggested that avoids the difficult problem of estimating the lead-vehicle deceleration; using instead other measurable quantities such as range and range-rate.

### INTRODUCTION

The pre-crash situation of two vehicles initially traveling at the same speed in the same direction when the lead vehicle begins to brake has been investigated by others. None of these investigations to date, however, have provided a complete, experimentally based algorithm that applies to all variations of the inter-vehicular dynamics. One recent experiment using the Iowa Driving Simulator (IDS) tested driver responses to a stationary vehicle in the lane of travel (ref. 1). Half of the drivers in this experiment were provided with collision warning advice and the other half were not.

This collision warning was based on a presumed driver/vehicle model which consisted of the following premises:

- Issue a warning to the driver at a time based on initial speed so that a constant-deceleration

stop could be completed in time to bring the following vehicle to a stop at a distance of 6.67 ft. behind a stopped lead vehicle.

- Assume a constant following-vehicle deceleration of 0.75g (the value used in the IDS tests), where  $g = 32.2 \text{ ft/sec}^2$ ,
- Assume a driver delay of 1.5 seconds between collision warning and brake activation.

The results from this experiment suggest that a collision warning would be effective in reducing the number of such collisions (see Appendix A for details). This warning could also be used to activate a warning when both vehicles are initially moving. However, as will be shown later, these warnings would not be timely. Although the relationship itself is not appropriate for situations where both vehicles are moving, the logic behind such a warning may still be useful.

To achieve the purpose of this report there are two objectives: 1.) Extend the results of the Iowa experiment to driving situations where both vehicles are initially moving at the same speed to cover all possibilities, and 2.) determine suitable warning logic for each situation. No experimental database such as that discussed above for stationary vehicles exists for situations where both vehicles are moving at the beginning of an imminent crash.

This study has three parts. The first part is the separation of conditions at the onset of lead-vehicle braking into sets which correspond to distinct types of relative motion between the vehicles. The second part is to develop the mathematical formulas which can be used to activate a warning for each of these three types of distinct relative motion. In the third part, the results of the first two parts are combined to form a description of

the conditions at which an imminent collision warning should be activated.

### NOTATION AND DYNAMICS

For this analysis, consider two vehicles initially moving at the same speed in the same direction (e.g., they are platooning). Both vehicles are assumed to initially be traveling with the absolute speed,  $V_0$ , and separated by a distance, or range, of  $R_0$ . The relationship of the two vehicles and the corresponding dynamic variables are shown in Figure 1, with the notations below.

#### Variables and Constants

R	range(ft)
X	position(ft)
V	absolute speed(ft/sec)
t	time(sec)
d	deceleration(ft/sec <sup>2</sup> )
dR/dt	range rate(ft/sec)
g	standard acceleration of gravity
C	smallest headway
T <sub>h</sub>	initial headway(sec)

#### Subscripts

0	initial, when t = 0
B	brakes on
F	following
L	lead
S	stopped
W	warning

The relative stopping dynamics begin at time  $t = 0$ , when the lead vehicle first applies its brakes and begins a constant deceleration to zero speed. The application of the lead-vehicle brakes determines the location of the reference for the measurement of all positions - this reference point is the location of the following-vehicle front bumper at the instant that the lead vehicle begins to brake. Time  $t = 0$  also sets the initial headway range,  $R_0$ . Hence, the position of the vehicles is indicated by the Cartesian coordinate,  $X$ , measured with respect to the fixed inertial reference at time  $t = 0$ . Note that  $X_F$  is measured to the following-vehicle front, and  $X_L$  to the lead-vehicle rear.

At an appropriate time  $t = t_w$ , a warning is issued to the driver of the following vehicle advising of a potential collision with a lead vehicle in the lane ahead. In keeping with the logic above, the time of the warning is based on the assumption that it will take the following driver 1.5 sec. to apply the brakes and that the driver will create a deceleration level of  $0.75g$ . The driver of the following vehicle then brakes at a constant deceleration. The time at which the following-vehicle brakes are applied is

$$t_{FB} = t_w + 1.5 \text{ sec.} \tag{1.}$$

However, before the warning is issued, the lead vehicle may or may not be at a stop in the lane ahead. In fact, it is necessary to first determine this condition in order to determine the proper time

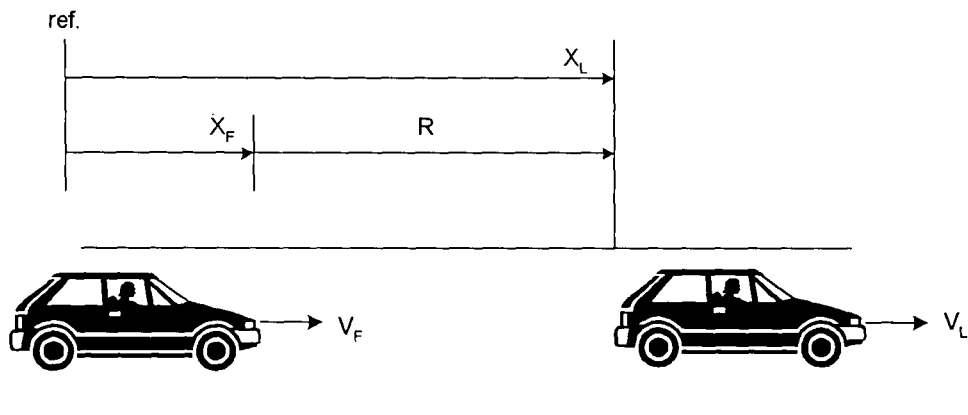


Figure 1. Two Vehicle Platooning Geometry.

for the collision warning to be issued to the following vehicle.

For all times after  $t = 0$ , the two vehicles continue their motions until they collide or are both stopped. At all times, the range,  $R$ , and the range rate,  $dR/dt$ , have the following relations:

$$R = X_L - X_F, \quad (2.)$$

$$dR/dt = V_L - V_F. \quad (3.)$$

## TYPES OF RELATIVE MOTION

The pattern of relative motion between the two vehicles is completely determined by the initial conditions at the onset of braking by the lead vehicle, at the time  $t = 0$ . At this time, the three parameters which set the pattern of relative motion are the initial speed ( $V_0$ , the same for both vehicles), the initial headway between the two vehicles, ( $T_h = R_0/V_0$ ), and the level of deceleration taken by the lead vehicle ( $d_L$ , presumed to be a constant but unknown value in the present analysis). Given these conditions, only three types of relative motion are possible. These relative motions are:

1. The warning is issued to the following vehicle after the lead vehicle stops. This is the case with a large initial headway.
2. The warning is issued before the lead vehicle stops, and the lead vehicle stops *before* the following vehicle stops.
3. The warning is issued before the lead vehicle stops, but the lead vehicle stops *after* the following vehicle stops.

An example of Relative Motion 1 is shown in Figure 2, where it is plotted in both Cartesian coordinates ( $V$ ,  $t$ ) for each vehicle, and relative range coordinates ( $R$  and  $dR/dt$ ). Note that the range plot is parametric in time,  $t$ , with  $t = 0$  at the highest point where the curve intersects the range axis. Range/range-rate plots of this type were first introduced by Fancher (ref. 2) and will provide an insightful means to present the collision warning metrics later in this report.

Relative Motion 1 may be understood by considering the events shown along the time axis in Figure 2. This sequence of events is initiated by the lead vehicle applying its brakes at  $t = 0$  and uniformly decelerating to a stop at  $t = t_{LS}$ . However, the initial headway is large enough so that the following vehicle does not receive a warning until

some time,  $t_w$ , well after the lead vehicle has stopped. Following the warning, it takes the following driver 1.5 seconds to apply the brakes at time  $t_{FB}$  and then uniformly brake to a stop at time  $t_{FS}$ .

An example of Relative Motion 2 is shown in Figure 3. In this case, the events are again started by the lead vehicle first applying its brakes, but now the lead vehicle comes to a stop *after* the warning is issued and *before* the following vehicle stops. Note that this includes a period during which the two vehicles are braking at the same time.

An example of Relative Motion 3 is shown in Figure 4. Here the lead vehicle comes to a stop *after* the following vehicle. This situation will give rise to the near approach of the two vehicles as the following vehicle decelerates rapidly to avoid the collision. The smallest headway occurs at time  $t_c$  when the relative speed between the two vehicles is zero. Note that this motion can only occur if the following vehicle has a greater deceleration than the lead vehicle.

We now focus our attention on the two boundaries between the above three types of relative motion in order to further clarify the motions. These boundaries are a critical element in determining the equations governing when the warning should be issued.

## BOUNDARY ANALYSIS

Boundary 1-2 divides Relative Motions 1 and 2, and occurs when a warning is issued at the instant of time that the lead vehicle comes to a stop. This means that the total distance traveled by the following vehicle after the lead vehicle begins to brake at  $t = 0$  equals the initial separation, plus the distance needed by the lead vehicle in coming to a stop, minus a 2 meter final separation. In equation form this is

$$X_{FS} = R_0 + \frac{1}{2} V_0^2 / d_L - 6.67 \quad (4.)$$

However, from another point of view, the distance traveled by the following vehicle also consists of three parts, these being the distance traveled while the lead vehicle is stopping, the distance traveled during the 1.5 sec. delay in brake application, plus the distance traveled while stopping itself at constant deceleration. This is

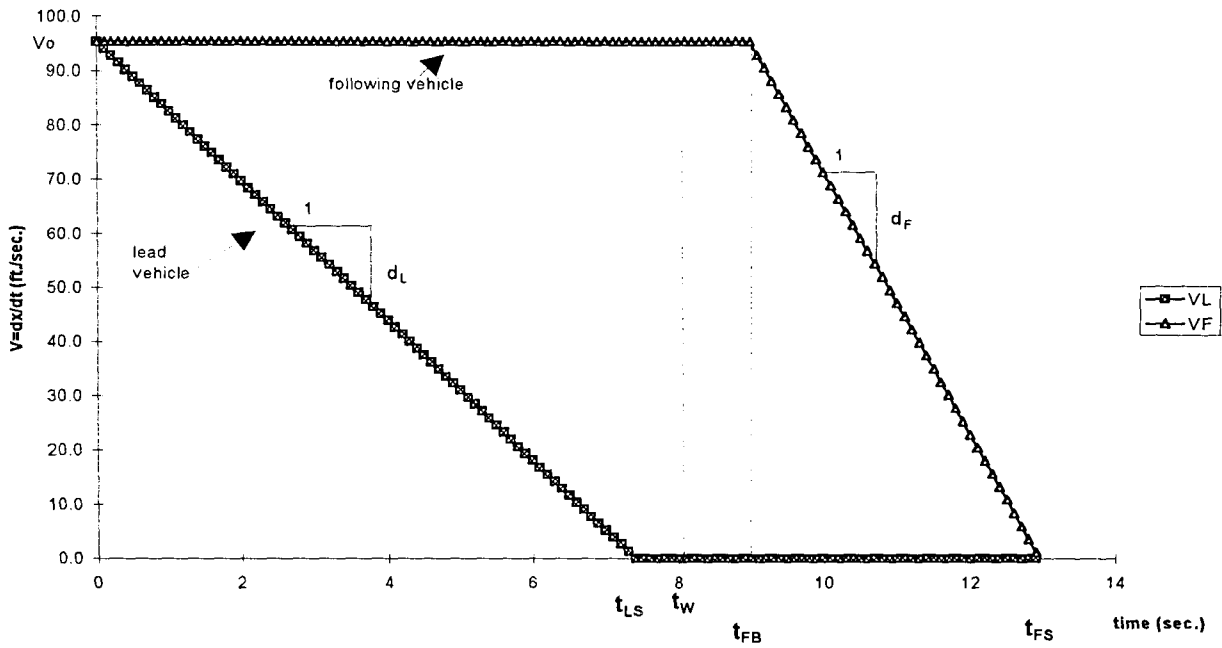


Figure 2(a). Velocity Plot. Example of Relative Motion 1 - Lead Vehicle Stops Before Warning.

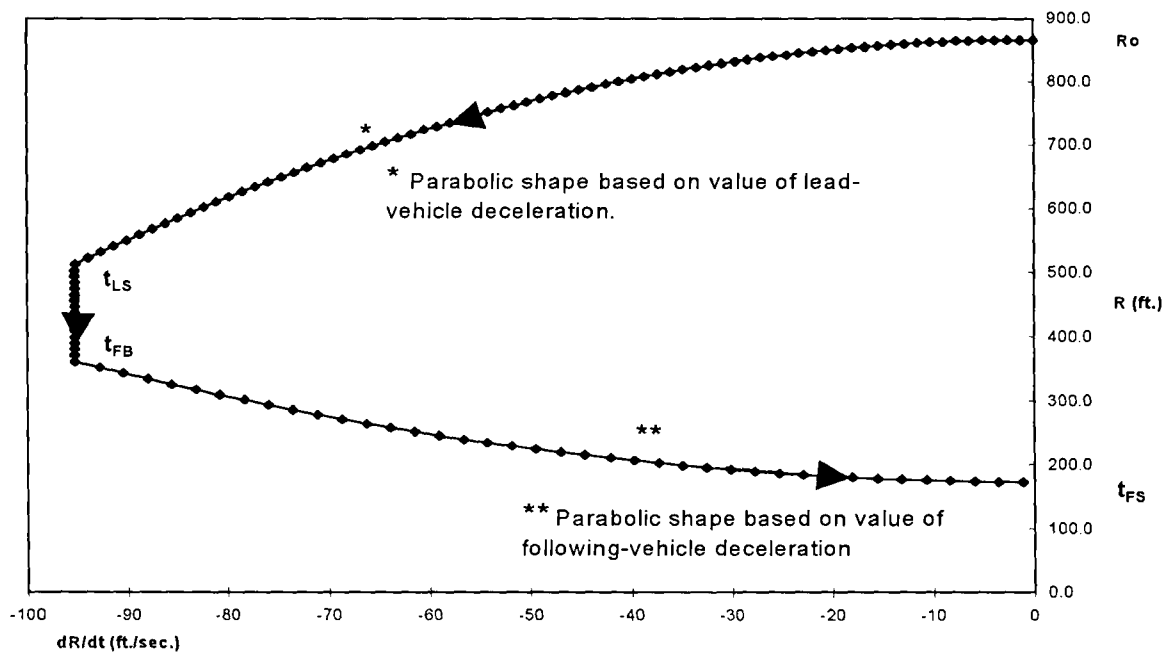


Figure 2(b). Range, Range Rate Diagram. Example of Relative Motion 1 - Lead Vehicle Stops Before Warning.

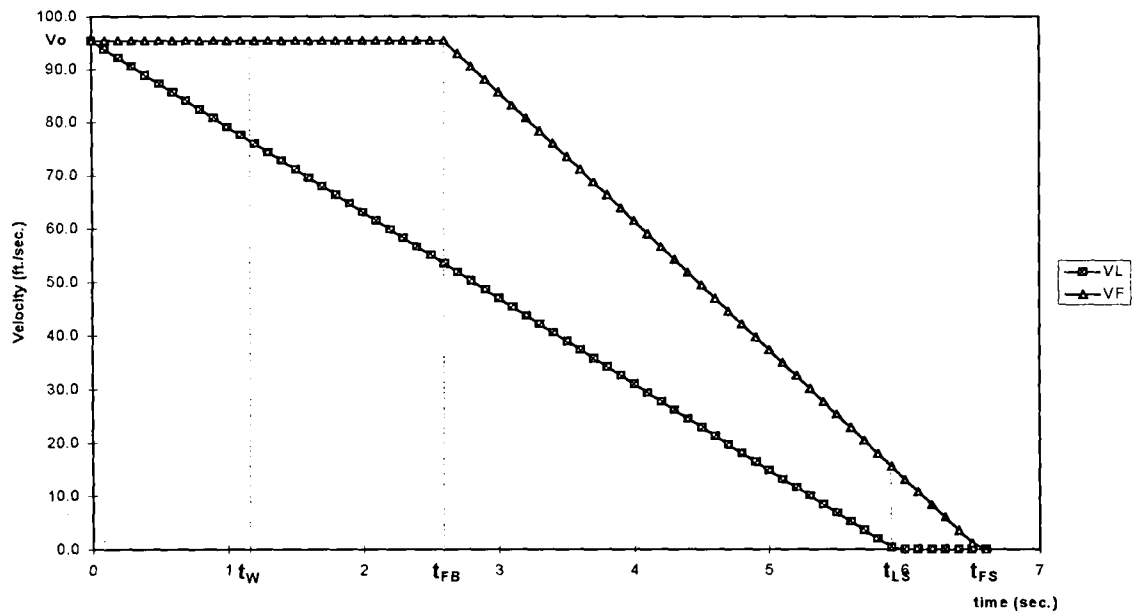


Figure 3(a). Velocity Plot. Example of Relative Motion 2- Lead Vehicle Does Not Stop Before Warning.

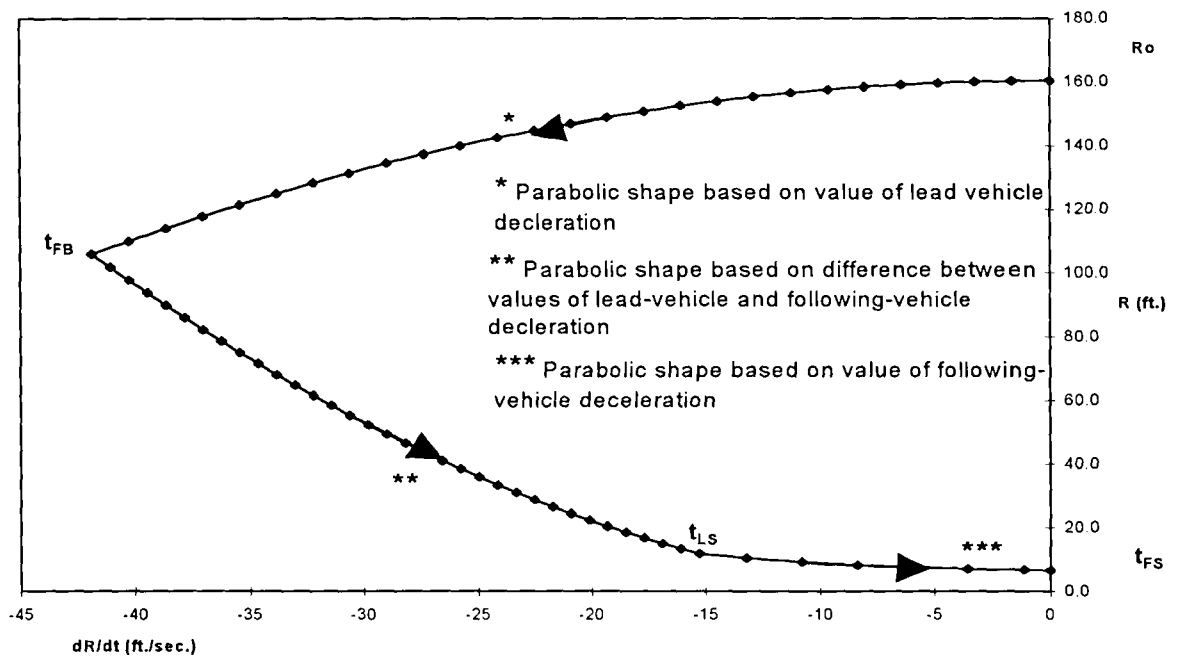


Figure 3(b). Range, Range Rate Diagram. Example of Relative Motion 2- Lead Vehicle Does Not Stop Before Warning.

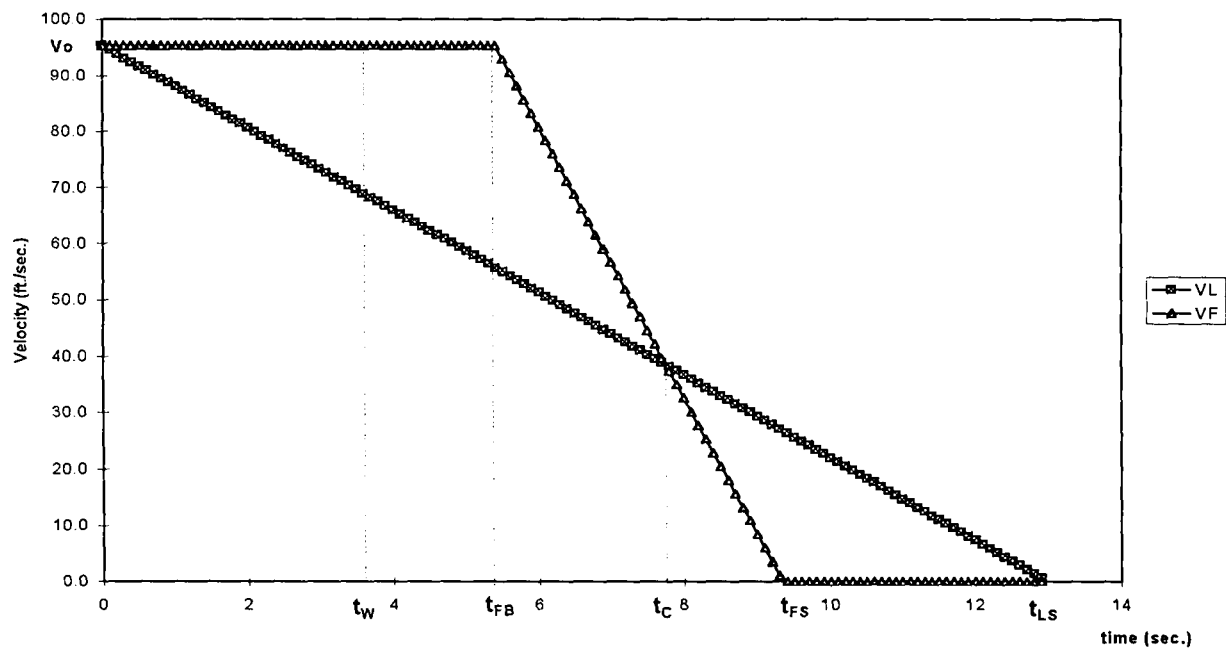


Figure 4(a). Velocity Plot. Example of Relative Motion 3 - Following Vehicle Stops Before Lead.

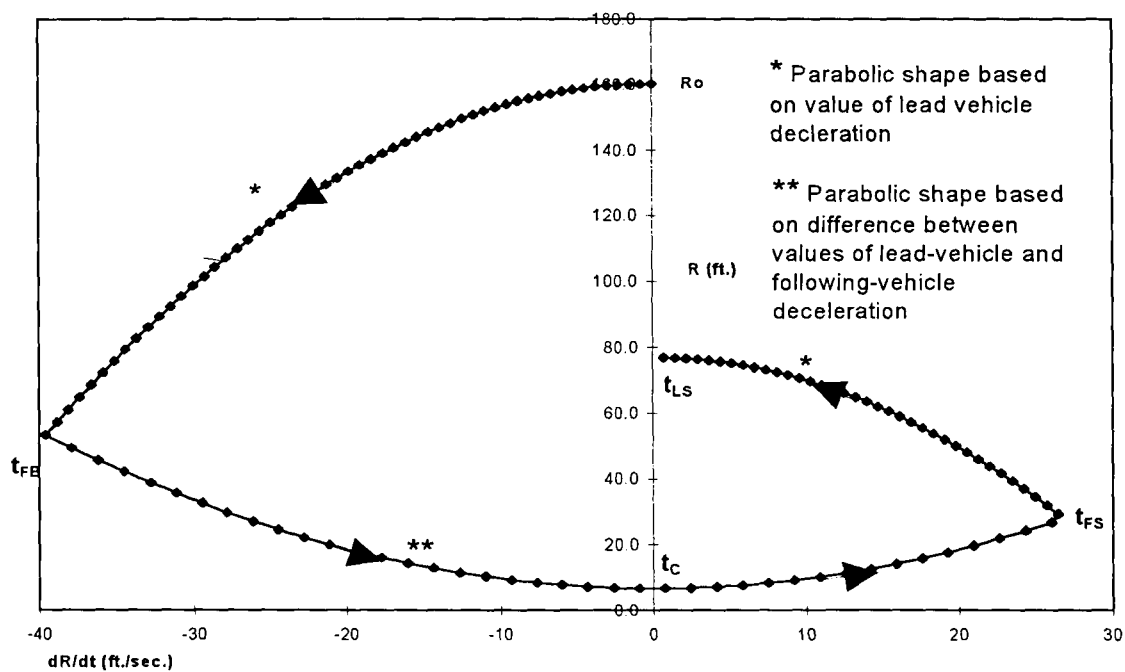


Figure 4(b). Range, Range Rate Diagram. Example of Relative Motion 3 - Following Vehicle Stops Before Lead.

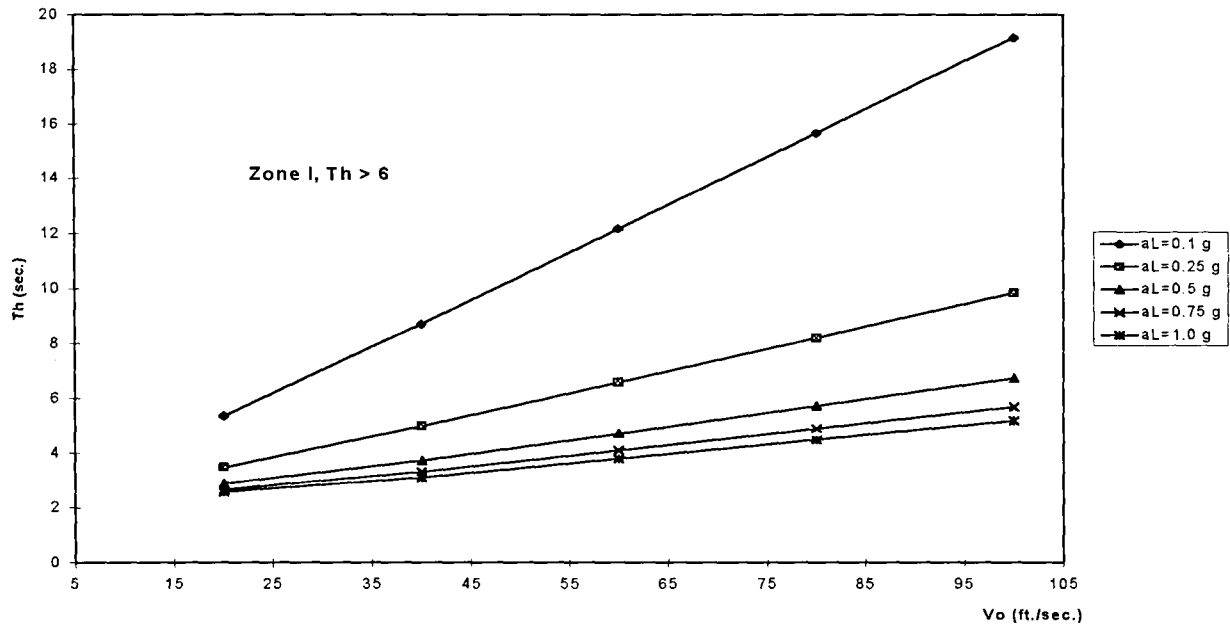


Figure 5. Plot of Boundary 1-2 Initial Conditions (Zone I as a function of  $a_L$ ).

$$X_{FS} = V_0^2 / d_L + 1.5V_0 + \frac{1}{2} V_0^2 / d_F \quad (5.)$$

When Eqns. 4 and 5 are combined and solved for the initial headway ( $T_h = R_0/V_0$ ), we find that the expression is

Initial headway,

$$T_h = \frac{1}{2} V_0 (1/d_L + 1/d_F) + 6.67/V_0 + 1.5 \quad (6.)$$

(The details of this derivation are included in Appendix B). So, given that  $d_F = 0.75g$ , the initial conditions ( $T_h$  versus  $V_0$ ) may be plotted for various values of  $d_L$ , as is done in Figure 5.

The meaning of Figure 5 is that, for a given value of lead-vehicle deceleration,  $d_L$ , if the initial conditions of velocity and headway are plotted on this diagram and create a point above the line for that deceleration, then the lead vehicle will be stopped before a warning needs to be issued. In this case, the criteria for a stopped vehicle ahead should be used -- this will be called Warning Criteria 1, and will be developed in the next section of this report. However, if the initial conditions are at a point below the corresponding deceleration line, then a warning is needed before the lead vehicle comes to a stop -- these conditions will lead to Warning Criteria 2 to be developed below.

Boundary 2-3 as shown in Figure 6 occurs when the two vehicles stop at the same instant of time. For this case, a similar development to that for Eqn. 6 may be used to find the expression for the headway - this gives

$$T_h = \frac{1}{2} V_0 (1/d_L - 1/d_F) + 6.67/V_0 \quad (7.)$$

Eqn. 7 is plotted in Figure 6 and derived in Appendix C. Again, for a given level of lead vehicle deceleration,  $d_L$ , when the initial conditions of velocity and headway are at a point above the corresponding deceleration line, then the lead vehicle stops first. If the initial condition point is below the corresponding deceleration line, then the following vehicle stops first. The equations for these warning criteria are developed in the next section of this report.

Figs. 5 and 6 are aspects of a single three-dimensional relationship between  $V_0$ ,  $T_h$ , and  $d_L$ . In order to clarify this relationship, consider the example shown in Figure 7 for the case of  $d_L = 0.5 g$ . Here the two boundary lines from Figs. 5 and 6 for this case of deceleration are plotted on the same axes of  $V_0$  and  $T_h$ , thus separating the  $V_0$ - $T_h$  space into three zones. Also shown in Figure 7 is the location of points corresponding to a constant value of range



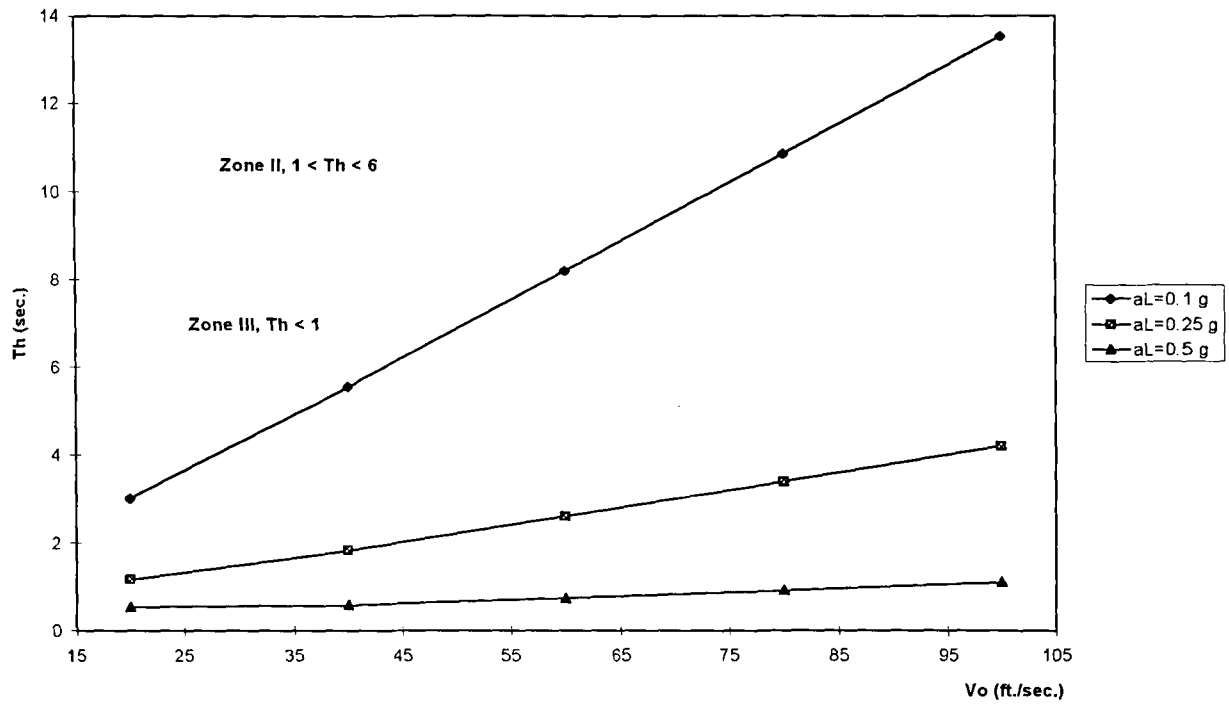


Figure 6. Plot of Boundary 2-3 Initial Conditions.

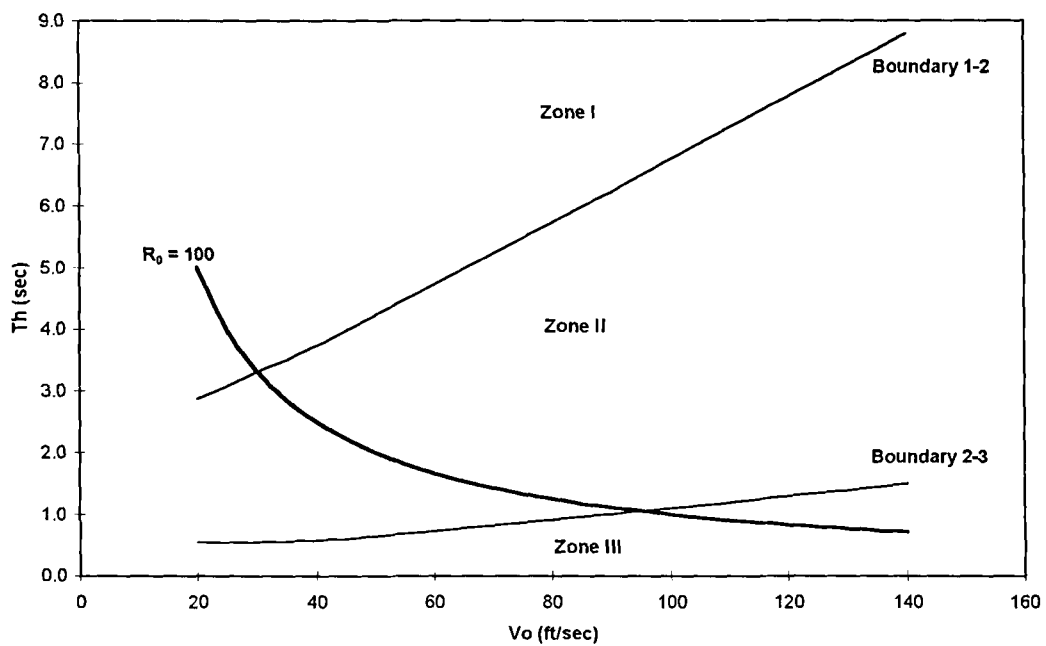


Figure 7. Example Initial Conditions Plot for  $d_L = 0.5g$ .

of 100ft. The three zones shown in the figure are each governed by different equations for warning criteria which are derived below. Zone I is for the cases where the warning is issued after the lead vehicle stops, Zone II is for cases where a warning is issued before the lead vehicle comes to a stop and the lead vehicle stops before the following vehicle, while Zone III is for the cases when the lead vehicle stops last.

## CRITERIA FOR ISSUING A WARNING

**Zone I** This zone is for those situations where the lead-vehicle is stopped before a warning is needed, leading to Warning Criteria 1. Recall that  $t = 0$  occurs when the lead vehicle first applies its brakes; however, since it is likely to be difficult or impossible to tell when the lead vehicle first applied its brakes (very large headway cases), we must rely on a simple range criteria for this zone based on the expected stopping distance of the following vehicle. That is, the warning range,  $R_w$ , must be based on the deceleration distance of the following vehicle, plus a 1.5 sec. lag to apply the brakes, plus the required 6.67 ft. safety margin. In equation form (using constant values as stated) this is

$$R_w = \frac{1}{2} V_0^2 / d_F + 1.5V_0 + 6.67$$

When  $d_F = 0.75g$ , this becomes

$$R_w = V_0^2 / 48 + 1.5V_0 + 6.67 \quad (8.)$$

which is the warning criteria used in the stationary vehicle Iowa experiment. Details of this experiment and the effectiveness of this warning are provided in Appendix A.

**Zone II** For situations where the lead vehicle is still stopping when the warning must be given, we must use another analysis, leading to Warning Criteria 2. Again,  $t = 0$  starts the analysis and sets the reference for all distances, with  $X = 0$  measured from the position corresponding to the following-vehicle's front bumper when  $t = 0$ . After  $t = 0$ , the lead vehicle uniformly brakes to a stop. However, for this zone, the following vehicle has a large enough initial headway that it continues on for a short while at constant speed until it reaches the warning time,  $t_w$ , at the warning range,  $R_w$ .

In this situation, the final location of the following vehicle,  $X_{FS}$ , is equal to the sum of the distance traveled before the warning, plus that after the warning before the brakes are applied, plus that to stop at constant deceleration. The final location of the lead vehicle,  $X_L$ , is equal to the initial headway plus the distance for it to decelerate. We can relate these to the required 2 meter, or 6.67 ft., separation required at the end of braking by the relationship

$$X_F = 6.67 - X_L \quad (9.)$$

Substituting for the appropriate terms allows us to find the warning time, range, and range rate, as is shown in Appendix D

$$t_w = \frac{1}{2} V_0 (1/d_L - 1/0.75) + (T_h - 1.5) - 6.67/V_0 \quad (10.)$$

$$R_w = R_0 - \frac{1}{2} d_L t_w^2 \quad (11.)$$

$$dR_w/dt = -d_L t_w \quad (12.)$$

**Zone III** In this zone, the warning is based on the closest approach of the two vehicles, which occurs while they are both still moving, thus leading to Warning Criteria 3. For these cases, the following vehicle stops before the lead vehicle, which is only possible due to the greater deceleration of the following vehicle. Now the warning criteria is based on the recognition that at some point during the braking maneuver, both vehicles will again be traveling at the same (slower) velocity at that time when they are in the nearest proximity (see Figure 4). Now, if the value of closest proximity is set equal to 6.67 ft., the resulting equations can be solved for the corresponding values of time, range, and range rate at which a warning should be issued--this is done in Appendix E. Thus,

$$t_w = \frac{[(0.75 - d_L)/0.75][2(V_0 T_h - 6.67)/\{d_L(1 - d_L/0.75)\}]^{1/2}}{-1.5} \quad (13.)$$

Equations (12.) and (13.) also hold for Zone III as well as Zone II.

It is now possible to overlay the three warning criteria developed above onto the three plots of range/range-rate previously shown in Figs. 2, 3 and 4. Examples of this are shown in Figure 8 for each of the three different zones. In order to generate these plots, it was necessary to pick specific values for the governing parameters  $d_L$ ,  $T_h$ , and  $V_0$ .

Note that the relative motion curves are parametric in time, with  $t = 0$  at the highest intersection of the plot with the range axis. The collision warning should be given at the time that the relative motion plot first intersects the warning curve.

The warning curves shown in Figs. 8(a), (b), and (c) correspond to initial velocities of 30, 60, and 120 ft/sec respectively with a constant lead-vehicle deceleration of 0.5g. The headway was allowed to vary and was stepped through a range of values. At each value of headway a test was made to determine which zone of initial conditions existed through the relationship depicted in Figure 7. When the zone changed, the warning range and range-rate equations were changed to the warning formulae for that zone.

### IMPLEMENTATION ISSUES

In application, a processor on board the following vehicle could continuously monitor the value of initial conditions on  $V_0$  and  $T_h$ . In the event of sensed lead-vehicle deceleration, the value of  $d_L$  is estimated and added to the processing algorithm and would trigger two calculations. The first calculation would be a determination of which of the three zones, or types of relative motion, is occurring based on initial conditions of  $V_0$  and  $T_h$  and the level of deceleration,  $d_L$ . This would be followed by a calculation of range and range rate at which a warning should be issued using the warning formulae that correspond to the type of relative motion, as derived above. This process is suggested by the overlay of the warning curves onto the relative motion plots shown in Figure 8. Although this implementation process is conceptually sound, it may not be practical due to the need to estimate the level of lead-vehicle deceleration. There are two computational issues here which are problematic: estimation of deceleration from samples of range and range rate data is a noisy process; and the calculation requires two or more samples, thus introducing delays of at least one sample period. However, these difficulties can be overcome by a simple, although previously unreported, change of perspective. The change is to use a  $d_L$ -based formulation instead of the  $T_h$ -based formulation shown thus far.

To accomplish this new formulation, the warning equations are generated by holding initial velocity and headway constant while allowing deceleration to vary. Graphically, this will create a warning range/range-rate plot which is parametric in lead-vehicle deceleration. While this seems like a slight difference from that above (parametric in headway), consider the advantage of storing a family of equations of warning criteria in terms of range versus range-rate for sets of initial conditions in velocity and headway. Now, since velocity and headway are easily measured values, the warning curves become look-ups which do not depend on lead-vehicle deceleration. Examples of such curves are shown in Figure 9. Here *each curve* is for constant values of initial velocity and headway for the full range of  $d_L$ . The stationary vehicle curve is included for reference. Thus,  $d_L$  never has to be estimated. This makes implementation vastly easier.

An example of the velocity-headway application is shown in Figure 10. In this case, the on-board processor could continuously calculate the warning criteria equations for range and range rate based on current values of velocity and headway. Then, any deceleration by the lead vehicle would produce a trajectory in range/range-rate that eventually intersects with the warning criteria. The point of the intersection would correspond to the unknown level of lead-vehicle deceleration. This means that the lead-vehicle deceleration does not have to be estimated regardless of the zone of motion. Thus, the benefits of using a warning algorithm that relies on knowledge of the lead-vehicle deceleration can be accomplished without actually doing the time-consuming computations that are necessary to produce an estimate. If there is a single important insight from this entire study, it is this latter point:

*The advantages and benefits of using a warning algorithm based on knowledge of the level of deceleration of the lead vehicle can be achieved without actually having to compute an estimate of the lead-vehicle deceleration.*

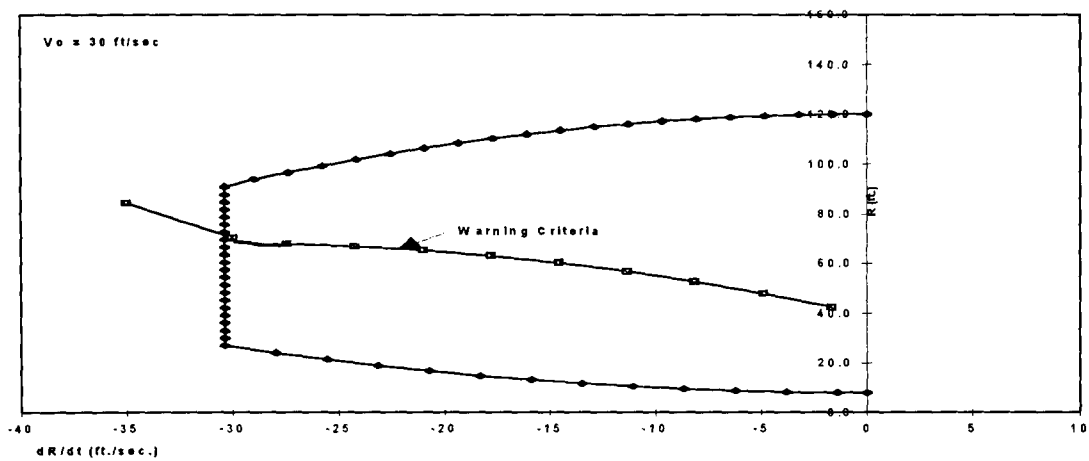


Figure 8(a). Examples of Warning Criteria Parametric in  $T_h$  for Relative Motion 1.

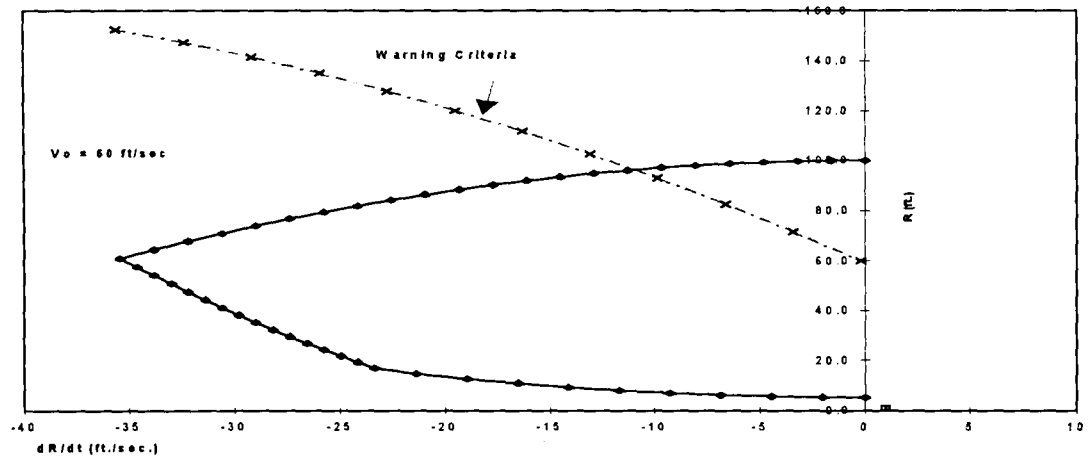


Figure 8(b). Examples of Warning Criteria Parametric in  $T_h$  for Relative Motion 2.

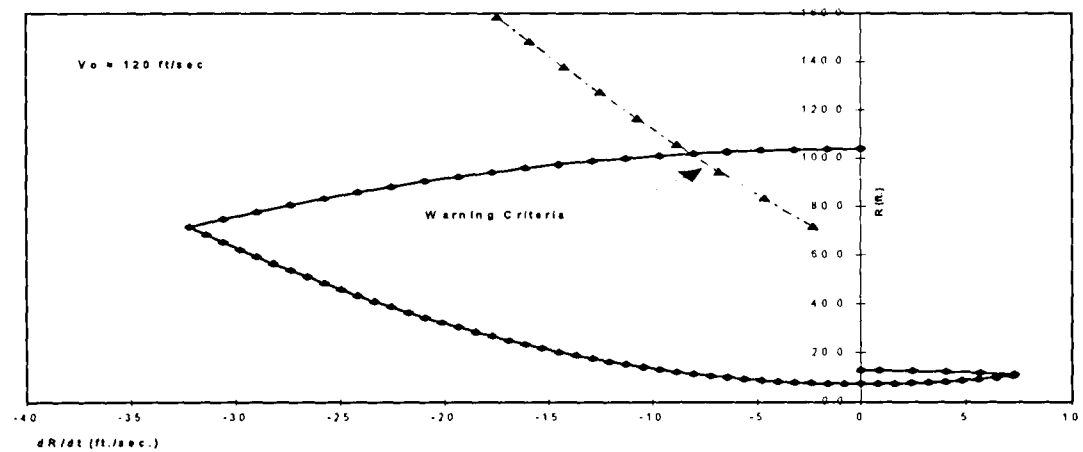


Figure 8(c). Examples of Warning Criteria Parametric in  $T_h$  for Relative Motion 3.

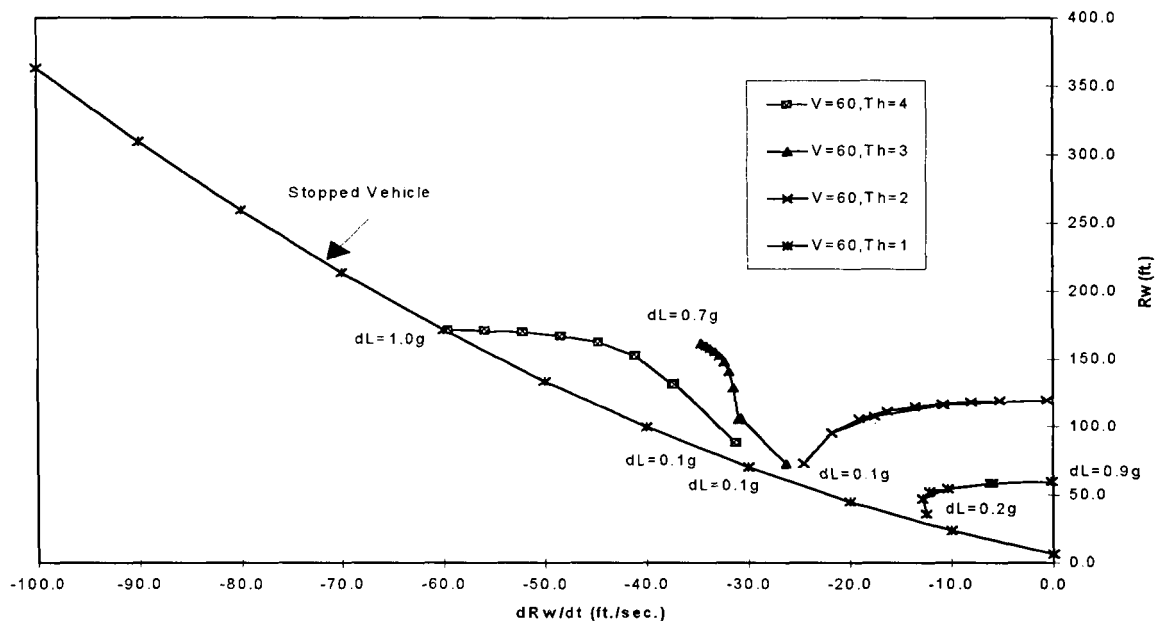


Figure 9. Warning Curves Parametric In Lead-Vehicle Deceleration.

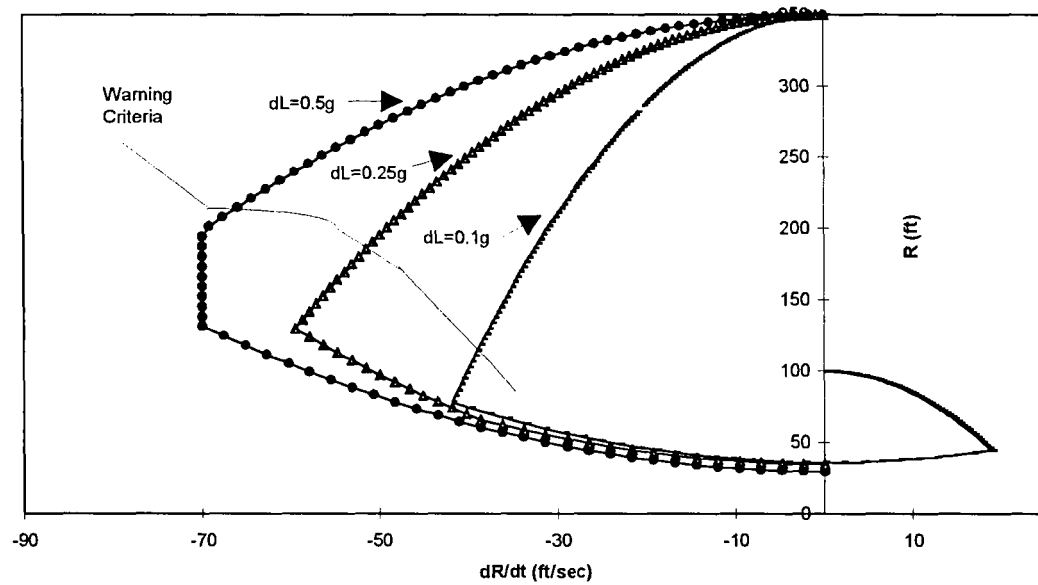


Figure 10. Example of the Warning Criteria for  $V_0=70$  ft/sec,  $T_h=5$  Relative Motion In All Zones.

## CONCLUSIONS

This report develops criteria for issuing warnings to drivers when a rear-end crash with a lead vehicle which is initially moving. The approach used here is to extend previous logic on a warning criteria which has been shown to be effective in situations where the driver is confronted with a stationary vehicle in the travel lane. As such, analysis is given to the logic in situations where two vehicles are initially traveling at the same speed prior to braking by the lead vehicle. The analysis shows that there are three distinct types of relative motion that can result, and that each type can be determined by examining the initial conditions at the time that the lead vehicle begins to brake. The appropriate values of warning range and range rate can then be determined for each type of motion. Examples of the location of these criteria in a range/range-rate diagram are shown in Figure 8 for example initial condition sets.

Finally, these results are extended to implementation where it is shown that the lead-vehicle deceleration need not be known to create an effective driver warning system.

In evaluating these results, several questions are suggested. Is it practical to use straight-line approximations in the range/range-rate warning criteria as a simplification (similar to the control law used in some adaptive cruise control systems)? Also, in a human factors sense, does this extension of a criterion from a stationary vehicle situation to

moving vehicle situations create a basis for a meaningful and effective warning to the driver? Similarly questions of variation in driver reaction time as well as system noise effects and roadway conditions are potential areas for enhancement of these findings.

## STS ACKNOWLEDGMENT

This work was based in part by the work done by Terry Wilson of Sensor Technologies & Systems, Inc. (formerly Frontier Engineering) and by Daniel V. McGehee of The University of Iowa which was sponsored by the National Highway Traffic Safety Administration (NHTSA), U.S. Department of Transportation under contract No. DTNH22-93-C-07326.

## REFERENCES

1. McGehee, D.V., Brown, T.I., Wilson, T.B., and M. Burns (1997), "Examination of Driver's Collision Avoidance Behavior in a Lead Vehicle Stopped Scenario Using a Front-to-Rear-End Collision Warning System," *Sensor Technologies & Systems, DOT/NHTSA Technical Report, Contract No. DTNH22-93-C-07326*.
2. Fancher, P. and Bareket, Z. (1994), "Controlling Headway Between Successive Vehicles," *Proceedings of the Association for Unmanned Vehicle Systems Annual Meeting* (pp.149-157), Detroit, MI.

## APPENDIX A: THE STOPPED-LEAD-VEHICLE SCENARIO TEST

### Introduction

The objective of this study was to investigate how drivers with and without rear-end collision warning systems react when purposefully distracted just when a stationary vehicle is revealed. The test was conducted using the Iowa Driving Simulator equipped with a driver warning system that provided auditory warnings based on two different warning criteria. A total of 30 subjects was split across three conditions with 10 subjects each. The two warning distances resulted from use of two values of driver reaction time for a hypothetical average driver.

Driver collision avoidance performance was compared to that in the baseline condition where no warning was present. Results showed that the collision warning system in the long warning condition showed shorter accelerator release reactions times, fewer crashes, and less severe crashes compared with both the baseline condition and the short warning condition. Experimental evidence suggests that the short warning condition may also have distracted drivers at the last moment after they had already begun to brake, resulting in some crashes. This is possibly a result of the warning display modality (auditory) and not a function of the timing of the warning.

### Background

This was the second of two tests to be carried out on the Iowa Driving Simulator. The first test consisted of a scenario where a lead-vehicle was in motion at the time of the collision.

### Warning Display

The primary warning alert was an auditory car horn icon.

### Warning Algorithm

The warning algorithm used was the stopping distance algorithm of the form:

$$WD = V_F^2 / 2d_F + T_d V_F + R \quad (A-1)$$

where,

WD Warning distance compared with sensor range to the lead vehicle

$V_F$  Following (host) vehicle absolute speed (measured)

$d_F$  Following (host) vehicle deceleration (assigned)

$T_d$  Warning time delay (assigned)

R Confidence interval (assigned).

WD is continuously calculated and compared to the measured headway between the host and lead vehicle. If the distance is less than the warning distance, a driver warning is activated.

For this study the following values were used:

$V_F$  Subject vehicle speed

$d_F$  0.75 g's (7.35 m/s<sup>2</sup>)

$T_d$  1.0 seconds (short), 1.5 seconds (long)

R 6.67 ft.

The stopping distance algorithm functions to bring the host vehicle to a stop at a distance R (6.67 ft.) behind the lead vehicle, when the driver has a reaction time of  $T_d$  (1.0 seconds short, 1.5 seconds long) and decelerates at a constant rate of 0.75g (7.35 m/s<sup>2</sup>).

### Experimental Procedure

To reduce anticipation of rear-end crashes, subjects were told that they would participate in a study to assess the fidelity of the simulator. Baseline subjects were given no further instructions. Subjects in the collision warning condition had the collision warning system explained to them before driving and then performed two "looming" maneuvers on a practice lead vehicle so they could see the collision warning function in operation. All participants were allowed a 5-minute practice drive.

After some initial driving along a freeway, the subjects came across a lead vehicle (a large truck.) The simulator scenario then "coupled": the subject vehicle with the truck at a 3.2 second headway. Once the vehicles were coupled, a digitized voice came over the vehicle's speakers and asked the driver to "press the button above the rear-view mirror until the red light comes on." Three hundred milliseconds after the driver pressed the button the truck swerved to the center lane and exposed a stopped passenger vehicle in the right lane. Corresponding to the swerve of the truck, the

collision warning display (auditory horn) was actuated using one of the two warning times.

### **Results and Discussion**

Drivers chose many strategies besides just braking to avoid the stationary vehicle. Results showed that the collision warning system in the long warning condition showed shorter accelerator release reactions times, fewer crashes, and less severe crashes compared with both the baseline condition and the short warning condition. Experimental evidence suggests that the short warning condition also may have distracted drivers at the last moment, resulting in some crashes. This is possibly a result of the warning display modality (auditory) and not a function of the timing of the warning.

### **Conclusions**

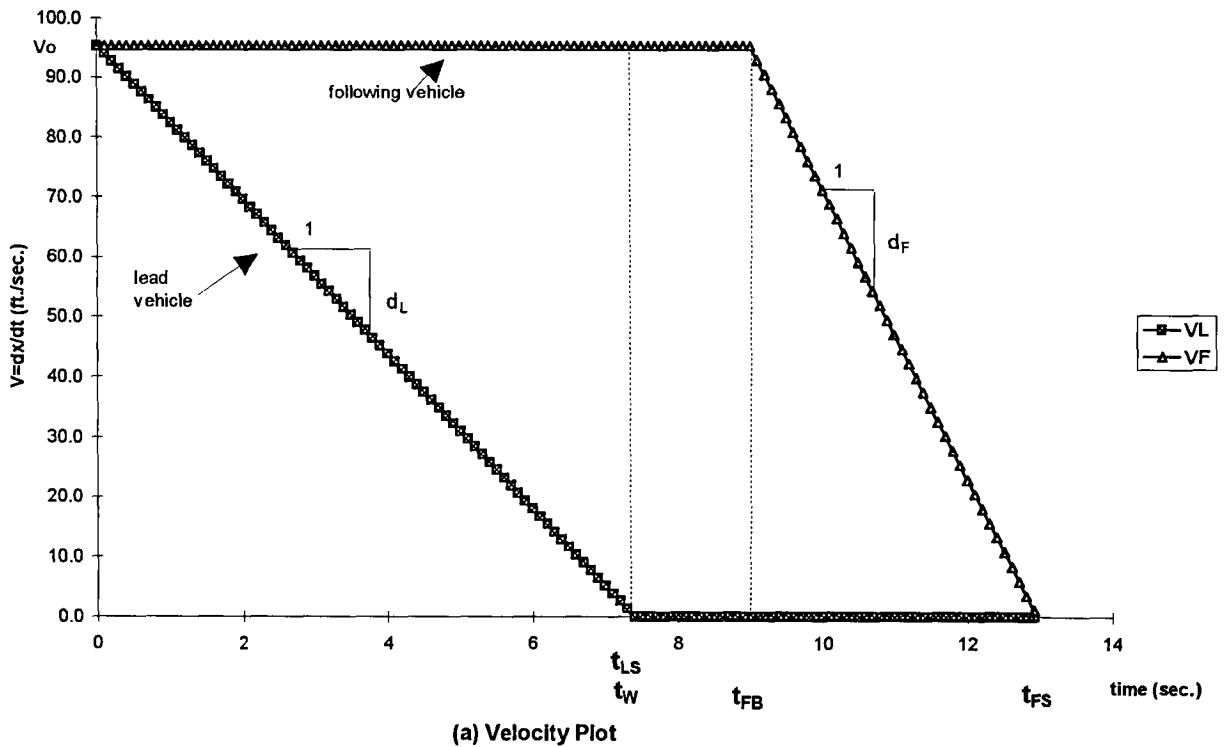
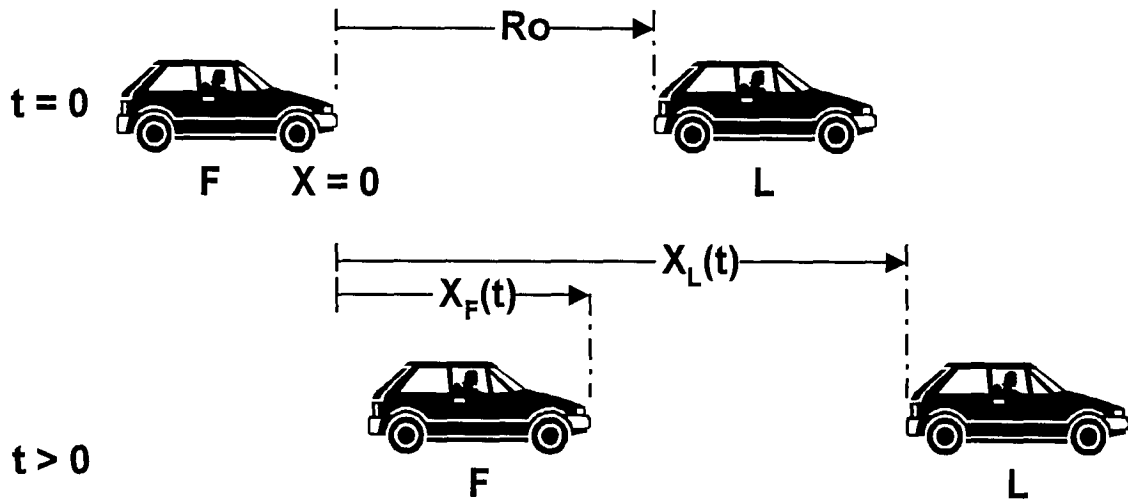
This study showed that the timing of a warning is important in the design of collision warning systems. Furthermore, data suggests the potential to provide a disbenefit to drivers if the warning alert is done improperly.

### **Reference**

Daniel V. McGehee and Timothy I. Brown of The University of Iowa., Terry B. Wilson and Mike Burns of Sensor Technologies & Systems (Formerly Frontier Engineering), "Examination of Driver's Collision Avoidance Behavior in a Lead Vehicle Stopped Scenario Using a Front-To-Rear-End Collision Warning System," DOT/NHTSA Technical Report, Contract DTNH22-93-C-07326, September 19, 1997.



# APPENDIX B: ANALYSIS FOR BOUNDARY 1-2



(a) Velocity Plot

Figure B-1 Timing of Events for Boundary 1-2.

Criteria

The lead vehicle comes to a stop before following vehicle begins to brake. A

warning is issued at the same time that the lead vehicle stops. The following vehicle begins to brake 1.5 seconds after the warning is activated.

### Analysis

1) The warning time,  $t_w$ , is the value of first time at which  $dX_L/dt = 0$ , i.e.,

$$\begin{aligned} dX_L/dt &> 0 \text{ for } t < t_w \\ dX_L/dt &= 0 \text{ for } t > t_w \end{aligned}$$

2)  $X_F(t_{FS}) = X_L(t_w) - 6.67$  where  $t_{FS}$  is the time at which the following vehicle stops, i.e.,

$$\begin{aligned} dX_F/dt &> 0 \text{ for } t < t_{FS} \\ dX_F/dt &= 0 \text{ for } t > t_{FS}. \end{aligned}$$

By definition:

$$\begin{aligned} t_w &= V_0/d_L \\ X_F(t_w) &= V_0 t_w = V_0^2/d_L \end{aligned}$$

Also, the final positions of the two vehicles are,

$$\begin{aligned} X_F(t_{FS}) &= X_F(t_w) + 1.5V_0 + V_0^2/2d_F \\ X_L(t_w) &= R_0 + V_0^2/2d_L \end{aligned}$$

The relationship between the two final positions must be,

$$X_F(t_{FS}) = X_L(t_w) - 6.67$$

Substituting gives,

$$X_F(t_w) + 1.5V_0 + V_0^2/2d_F = R_0 + V_0^2/2d_L - 6.67$$

But, since,

$$\begin{aligned} X_F(t_w) &= V_0^2/d_L \\ V_0^2/d_L + 1.5V_0 + V_0^2/2d_F &= R_0 + V_0^2/2d_L - 6.67 \end{aligned}$$

Simplifying gives:

$$V_0^2/2[1/d_L + 1/d_F] + 1.5V_0 - R_0 + 6.67 = 0$$

However,  $R_0 = V_0 T_h$  where  $T_h$  is the headway between the two vehicles before any braking, i.e., when  $t < 0$ . Then:

$$V_0^2/2[1/d_L + 1/d_F] + V_0[1.5 - T_h] + 6.67 = 0$$

is the relationship that describes Boundary 1-2. This expression can also be written as:

$$T_h = 1.5 + V_0/2[1/d_L + 1/d_F] + 6.67/V_0.$$

## APPENDIX C: ANALYSIS FOR BOUNDARY 2-3

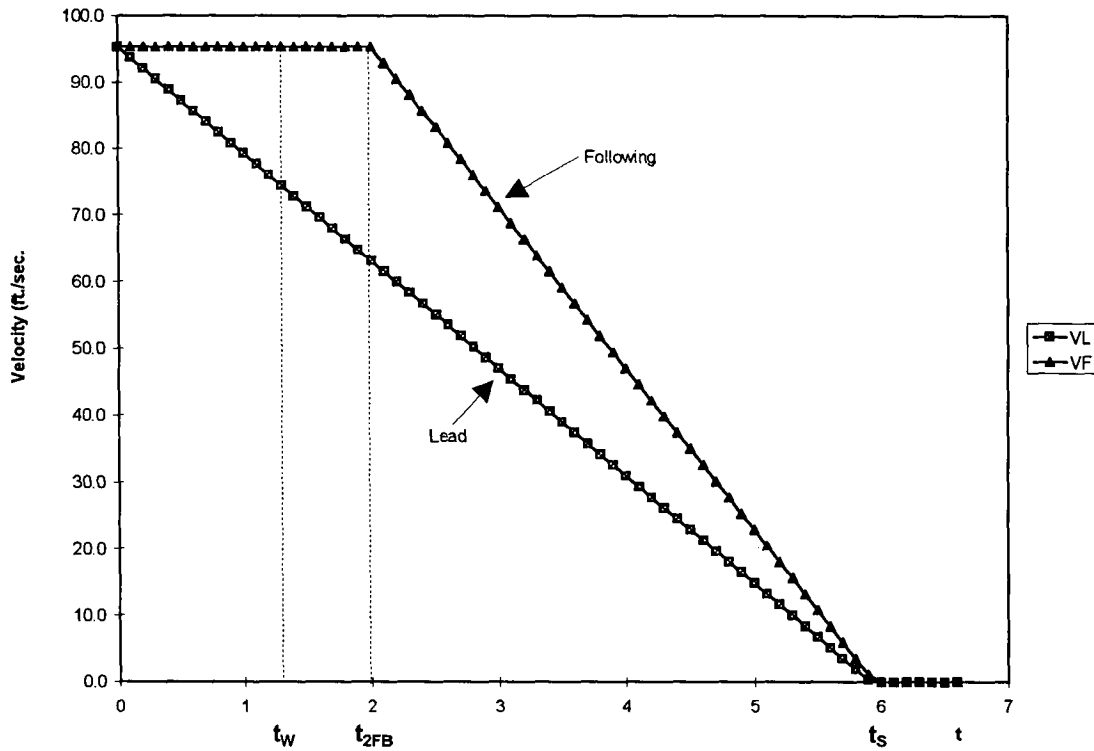


Figure C-1 Timing of Events for Boundary 2-3

### Criteria

Both vehicles come to a stop at the same time.

### Analysis

If the vehicles are 6.67 ft. apart when they come to rest, they must satisfy the end conditions:

$$X_F(t_s) = X_L(t_s) - 6.67$$

$$X_L(t_s) = R_0 + V_0^2/2d_L$$

$$X_F(t_s) = X_F(t_W) + 1.5V_0 + V_0^2/2d_F$$

Substituting the first two equations into the last gives:

$$X_F(t_W) + 1.5V_0 + V_0^2/2d_F = R_0 + V_0^2/2d_L - 6.67$$

Solving for  $X_F(t_W)$  and noting that  $R_0 = V_0 T_h$  gives

$$X_F(t_W) = V_0^2/2[1/d_L - 1/d_F] + V_0[T_h - 1.5] - 6.67$$

Also note that

$$X_F(t_W) = V_0 t_W$$

and

$$t_W = t_s - (t_s - t_{FB}) - (t_{FB} - t_W)$$

$$t_W = t_s - V_0/d_F - 1.5$$

and since  $t_s = V_0/d_L$ ,

$$t_W = V_0[1/d_L - 1/d_F] - 1.5$$

and

$$X_F(t_W) = V_0^2[1/d_L - 1/d_F] - 1.5V_0$$

Equating the expressions for  $X_F(t_W)$  we have:

$$V_0^2[1/d_L - 1/d_F] - 1.5V_0 = V_0^2/2[1/d_L - 1/d_F] + V_0[T_h - 1.5] - 6.67$$

Combining terms:

$$V_0^2/2[1/d_L - 1/d_F] + V_0 T_h + 6.67 = 0.$$

This is the relationship between the initial conditions for Boundary 2-3. Solving for  $T_b$  we have:

$$T_b = V_0/2[1/d_L - 1/d_F] + 6.67/V_0$$

## APPENDIX D: WARNING CRITERIA FOR ZONE 2

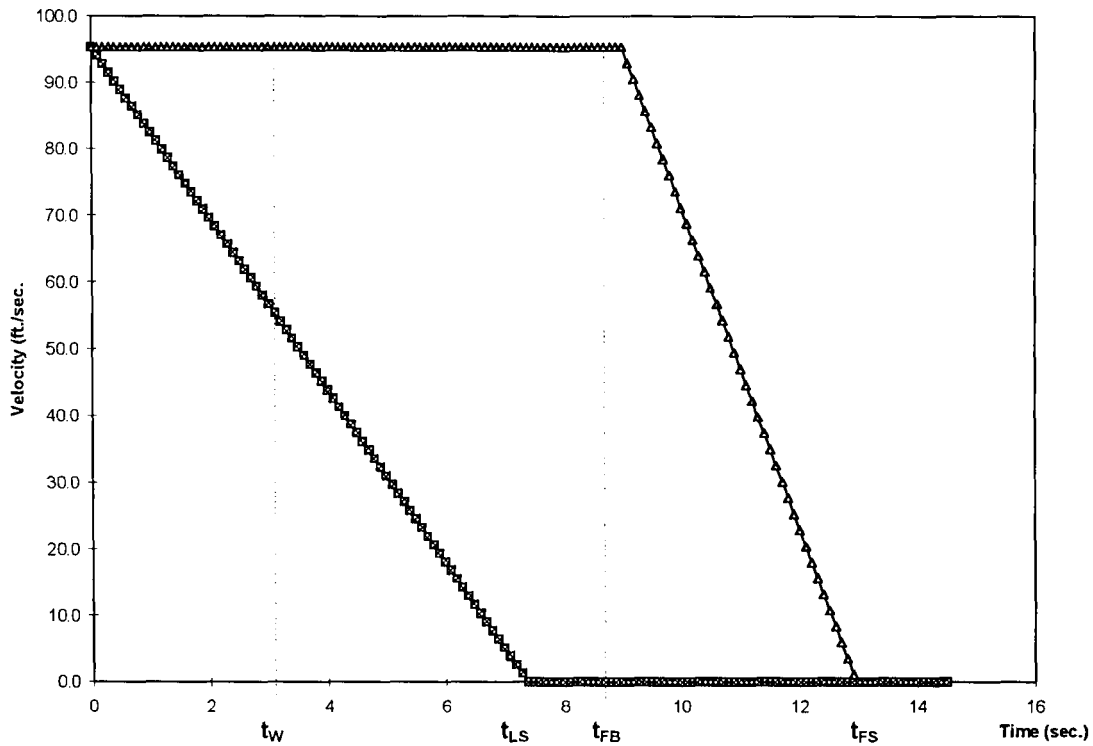


Figure D-1. Timing of Events for Zone 2 Motions

### Criteria

Lead vehicle comes to a stop before following vehicle, with the warning issued while the lead vehicle is braking.

### Analysis

At the end of the motion, the vehicles are assumed to be separated by 6.67 ft.:

$$X_F(t_{FS}) = X_L(t_{LS}) - 6.67$$

And their final positions are

$$X_F(t_{FS}) = V_0 t_w + V_0 (t_{FB} - t_w) + V_0^2 / 2d_F$$

$$X_L(t_{LS}) = R_0 + V_0^2 / 2d_L$$

Substituting into the first equation,

$$V_0 t_w + 1.5V_0 + V_0^2 / 2d_F = R_0 + V_0^2 / 2d_L - 6.67$$

Solving for  $t_w$  gives

$$t_w = V_0 / 2 [1/d_L - 1/d_F] - 1.5 + 1/V_0 [R_0 - 6.67]$$

But  $R_0 = V_0 T_h$  therefore,

$$t_w = V_0 / 2 [1/d_L - 1/d_F] + [T_h - 1.5] + 6.67 / V_0$$

The corresponding values of  $R_w$  and  $dR_w/dt$  at  $t = t_w$  are:

$$R_w = R_0 - d_L t_w^2 / 2$$

$$dR_w/dt = -d_L t_w$$

## APPENDIX E: WARNING CRITERIA FOR ZONE 3

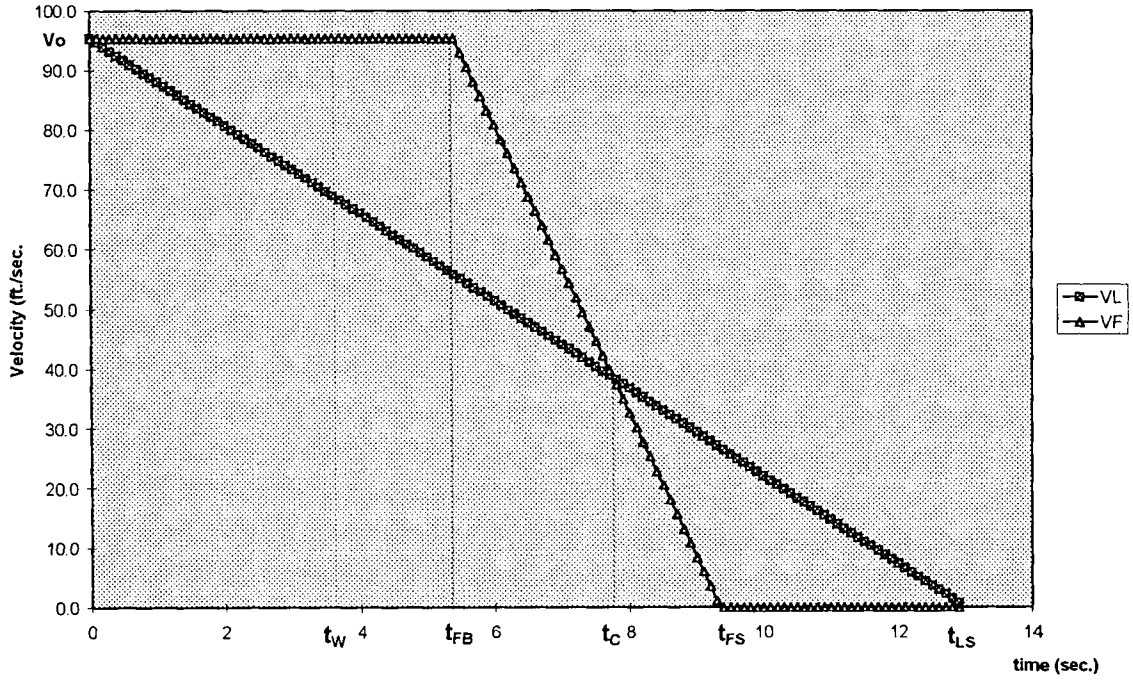


Figure E-1 Timing of Events for Zone 3 Motions

### Criteria

Following vehicle comes to a stop before lead vehicle. The closest approach occurs while the two vehicles are still in motion.

### Analysis

Here, the closest approach of the two vehicles occurs at time  $t_c$  and requires the following relationships:

$$X_F(t_c) = X_L(t_c) - 6.67 \quad (\text{E-1})$$

$$dX_L(t_c)/dt = dX_F(t_c)/dt, \quad (\text{E-2})$$

Also note that the closest approach occurs at the time when the range rate,  $dR/dt$ , changes sign,

$$\begin{aligned} dR/dt &< 0 & 0 < t < t_c \\ dR/dt &> 0 & t > t_c \end{aligned}$$

The position of the two vehicles at the closest approach is:

$$\begin{aligned} X_L(t_c) &= R_0 + V_0 t_c - (d_L/2)t_c^2 \\ X_F(t_c) &= V_0 t_c - (d_F/2)(t_c - t_{FB})^2 \end{aligned}$$

Substituting into eqn. E-1 above,

$$V_0 t_c - (d_F/2)(t_c - t_{FB})^2 = R_0 + V_0 t_c - (d_L/2)t_c^2 - 6.67 \quad (\text{E-3})$$

Further, the speed equations for the two vehicles at the critical time may be written as,

$$\begin{aligned} dX_L(t_c)/dt &= V_0 - d_L t_c \\ dX_F(t_c)/dt &= V_0 - d_F(t_c - t_{FB}) \end{aligned}$$

which may be equated at the critical time using eqn. E-2 above,

$$V_0 - d_L t_c = V_0 - d_F(t_c - t_{FB})$$

Rearranging this equation gives,

$$\begin{aligned} t_c(d_F - d_L) &= t_{FB}d_F \\ \text{and} \\ t_{FB} &= [(d_F - d_L)/(d_F)] t_c \quad (\text{E-4}) \end{aligned}$$

Substituting this into eqn. E-3 and simplifying gives,

$$-d_F/2[t_c - ((d_F - d_L)/(d_L))t_c]^2 = R_0 + V_0 t_c - (d_L/2)t_c^2 - 6.67$$

$$-d_F/2[d_L t_c/d_F]^2 = R_0 - 6.67 - (d_L/2)t_c^2$$

$$[d_L/2 - d_F/2(d_L/d_F)^2]t_c^2 = R_0 - 6.67$$

$$d_L/2 [1 - d_L/d_F]t_c^2 = R_0 - 6.67$$

$$\text{and } t_c = \{2(R_0 - 6.67)/\{d_L(1 - d_L/d_F)\}\}^{1/2}$$

Substituting into the eqn. E-4, and using

$$t_w = t_{FB} - 1.5$$

gives,

$$t_w = \{[(d_F - d_L)/d_F] [2(V_0 T_h - 6.67)/\{d_L(1 - d_L/d_F)\}]\}^{1/2} - 1.5$$

For  $0 \leq t \leq t_2$ , including  $t = t_w$

$$dR/dt = dX_L/dt - dX_F/dt = (V_0 - d_L t) - V_0$$

$$dR/dt = -d_L t$$

So, at the time of warning,

$$R_w = R_0 - (d_L/2)t_w^2$$

$$dR_w/dt = -d_L t_w$$

# APPLICATION OF A VIDEO ANALYZER FOR THE SAFETY EVALUATION OF AN INTELLIGENT CRUISE CONTROL SYSTEM

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## ABSTRACT

This paper describes the application of a video analyzer that was developed and used to evaluate the safety impact of an Intelligent Cruise Control (ICC) system. Naturalistic driving data were obtained from 10 vehicles identically equipped with the ICC and data acquisition systems. Volunteer drivers participated in the Field Operational Test (FOT) which was conducted in southeastern Michigan. The video analyzer was developed to assist in the determination of a set of driving scenarios, close calls, and driver reaction times for the driver test data.

The ICC FOT was the result of a cooperative agreement between the National Highway Traffic Safety Administration (NHTSA) and the University of Michigan Transportation Research Institute (UMTRI). Other parties contributing to the field operational test were Leica AG, the Michigan Department of Transportation, and Haugen Associates. The Volpe National Transportation Systems Center (Volpe Center) with support from Science Applications International Corporation (SAIC) conducted the independent evaluation for this FOT.

## INTRODUCTION

The Intelligent Cruise Control (ICC) Field Operational Test (FOT) consisted of 108 drivers, who had the ICC equipped vehicles for either two or five weeks. During the first week of the test, only manual control and conventional cruise control were available to the drivers. During the remaining weeks, manual control and ICC were available to the drivers. While the FOT was based in Ann Arbor, Michigan, the drivers were not restricted on where they could travel, as long as their travel was within the continental United States.

A major source of data collected in the ICC FOT was the video data recorded using the on-board camera. The video data recorded were stored as video clips. There were two types of video clips recorded - Exposures and Episodes. An exposure video clip has a duration of 2 seconds and was recorded once every 5 minutes that the vehicle was on. An episode video clip has a duration of 30 seconds and was recorded not on a regular basis, but whenever one of the video trigger thresholds was

exceeded. Brake interventions, near encounters and a press of the concern button all had the potential of triggering the recording of an episode video. For brake interventions (triggered by deceleration  $> 0.05$  g) and near encounters (required deceleration to ensure 0.3 sec headway  $> 0.05$  g), the video was recorded for 15 seconds before and 15 seconds after the event which triggered the video to be recorded. Pressing the concern button press was programmed to capture the 30 seconds of video prior to the concern point.

In determining the ways in which the data available from the FOT would be analyzed, the evaluation team specified several different measures that were only available or were most easily measured through analysis of the video clips. The evaluation team realized that there would need to be some formal procedure for completing this analysis which would result in consistent and accurate recording of the measures of interest. It was this identified need which spawned the development of the video analyzer.

The data classifications resulting from the use of the video analyzer were stored in a data base which was linked to the FOT evaluation data base. The evaluation data base is a customized data base developed from the raw numerical data collected in the FOT. The customized data base includes classification information from other tools developed by the evaluation team (road class, level of land use, level of service). In developing the customized evaluation data base, the raw data were manipulated and sampled to provide more manageable data accessibility and analysis.

This paper describes the video analyzer's purpose, interface design, and primary classification methods, and provides some sample applications using preliminary ICC FOT data. The paper also discusses potential extended uses of the tool.

## PURPOSE

The purpose of the video analyzer is to allow a human to classify visual data in an efficient, consistent and accurate manner. Potentially, use of a computer interface decreases the effort involved in recording/using the classification data as it allows automatic recording of classifications without manual annotation, and can format



the classification data without requiring further manual input for use in the evaluation. In addition, the use of a computer interface allows the analyst to view certain numerical data variables to aid in deciding between particular classifications.

## INTERFACE DESIGN

The video analyzer interface was designed, in iterative fashion, by and for the ICC FOT evaluation team, to meet the data needs of evaluation and the functional needs of the particular video analysis required of the evaluation. In order to determine these functions, members of the evaluation team reviewed the project study plan to determine exactly what information needed to be recorded. A movie viewer was used to run through a set of video clips, and classified those video clips using a pencil and paper to record the required information. The paper and pencil method proved to be tedious and redundant. This procedure did, however, provide many insights on what functions the video analyzer would need to provide, what information the tool would need to provide, and what information the tool would need to record.

Separate screens were needed for analyzing exposure clips and episode clips, to reduce confusion and to help the video analyst concentrate on the specific measures needed from each type of video clip. Specifically, an exposure video classification interface was devised to classify road class and level of service. The episode video classification interface was drawn up to classify driving states and close calls (frequency, severity and proximity), and measure response times. Both interfaces would be used to identify whether or not the video clip was a weather event (rain, road spray or snow) as these events can lead to inaccurate data being recorded.

The detailed design of the interface screens, and their underlying programming and data flows, were addressed through a series of prototypes. Basically, it was decided that the episode interface would need to provide information on what triggered the video to be recorded, the magnitude of the triggering event, and a timeline or time display to track the time into a video clip. On the remainder of the screen, several of the variables collected by the ICC vehicle were displayed to help differentiate between different driving situations and to help accurately measure response times. The consensus on the most useful variables were:

- the range vs. the rate of change in range to the vehicle being tracked by the ICC equipped vehicle;
- the velocity of the ICC equipped vehicle,  $V$ ;
- the velocity of the vehicle being tracked by the ICC vehicle,  $V_p$ ;
- the ICC equipped vehicle's throttle;

- the rate of change in range to the vehicle being tracked by the ICC equipped vehicle;
- tracking, a logical variable which is 1 when a vehicle is being tracked; and
- brake, a logical variable which is 1 when the brake is being applied.

The most useful way to represent these variables was to have them plotted on the screen and time synchronized with the video clip.

With respect to the exposure interface, it was not necessary to provide any additional information on the driving situation to the analyst, other than the actual exposure video clip.

Sample episode and exposure classification screens from the video analyzer are shown in Figures 1 and 2, respectively.

## CLASSIFICATION – EPISODE VIDEO CLIPS

The general procedure followed by the video analyst in classifying an episode video clip is outlined in Figure 3. Each step of this procedure is described individually in the sub-sections below.

### Usability

The usability of a video clip is determined by the clarity and content of the captured video. If the events captured in the video clip are not discernible due to weather, or no events occurred during the clip (for example, a car sitting in a parking lot), then the clip is labeled unusable by selecting the “unusable” button. Once a clip has been labeled unusable, no further analysis is required, with the exception of determining whether or not the clip showed evidence of being a weather event.

### Driving States

Four driving states have been identified as being of interest to this study (Robinson, et al., 1997). They are:

- following a same speed target vehicle;
- closing on a target vehicle;
- separating from a target vehicle; and
- cruising.

The first three states represent non-cruising states (lead vehicle present) and can be differentiated accurately using algorithms created by the evaluation team. For this reason, the analyst chooses between two simplified driving states, cruising (no lead vehicle present) and not cruising. Driving states are identified by selecting the appropriate driving state button.

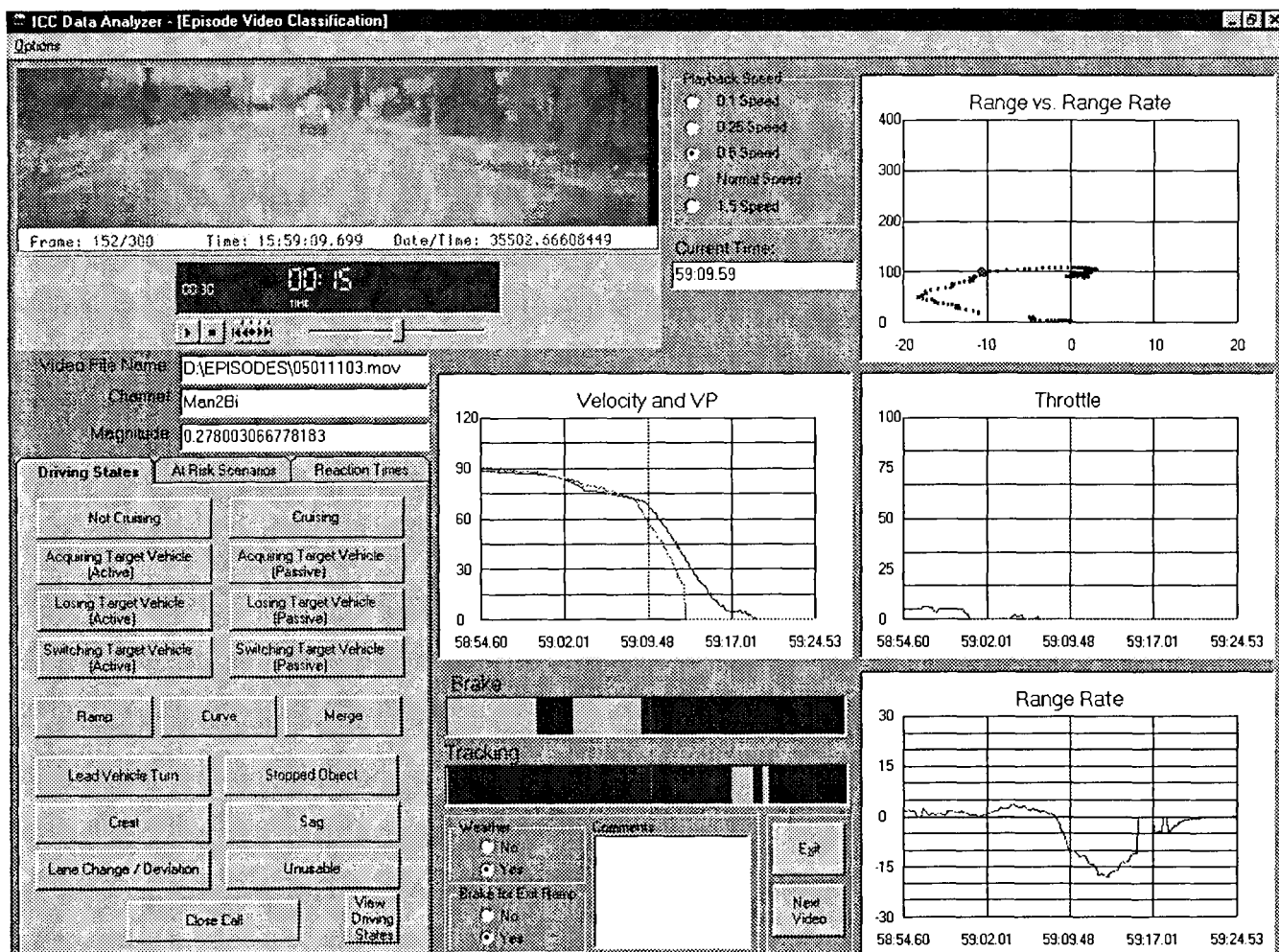


Figure 1. Sample Episode Screen.

## Transitions

Three transitions have been identified as being of interest to this study. They are:

- acquiring a target vehicle;
- dropping a target vehicle; and
- switching target vehicles.

By definition, all three of these transitions require a lane change to occur to qualify as a transition. If the lane change was performed by the ICC driver/vehicle then the transition is classified as being active. If the lane change was performed by another vehicle, then the transition is classified as being passive.

## Scenarios of Special Interest

Eight driving situations have been identified as being of special interest to this study. They are:

- driving on ramps;
- “not cruising” on curves;
- freeway merges;
- lead vehicle turns (left or right);
- stopped object on roadway;
- “not cruising” on crests;
- “not cruising” in sags; and
- unexplained lane changes or deviations.

Buttons are available on the Episode Video Interface to tag these scenarios of special interest.

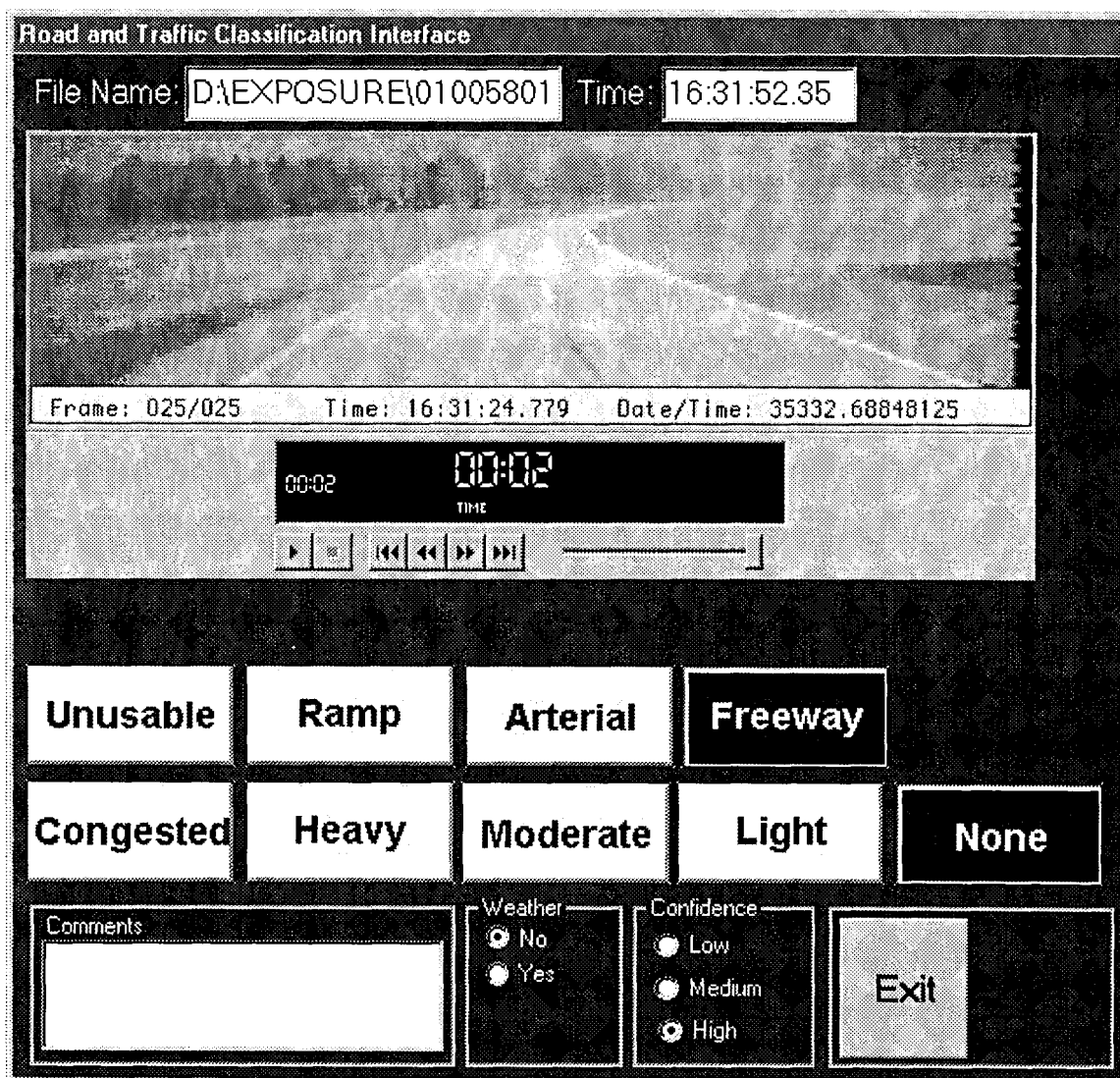


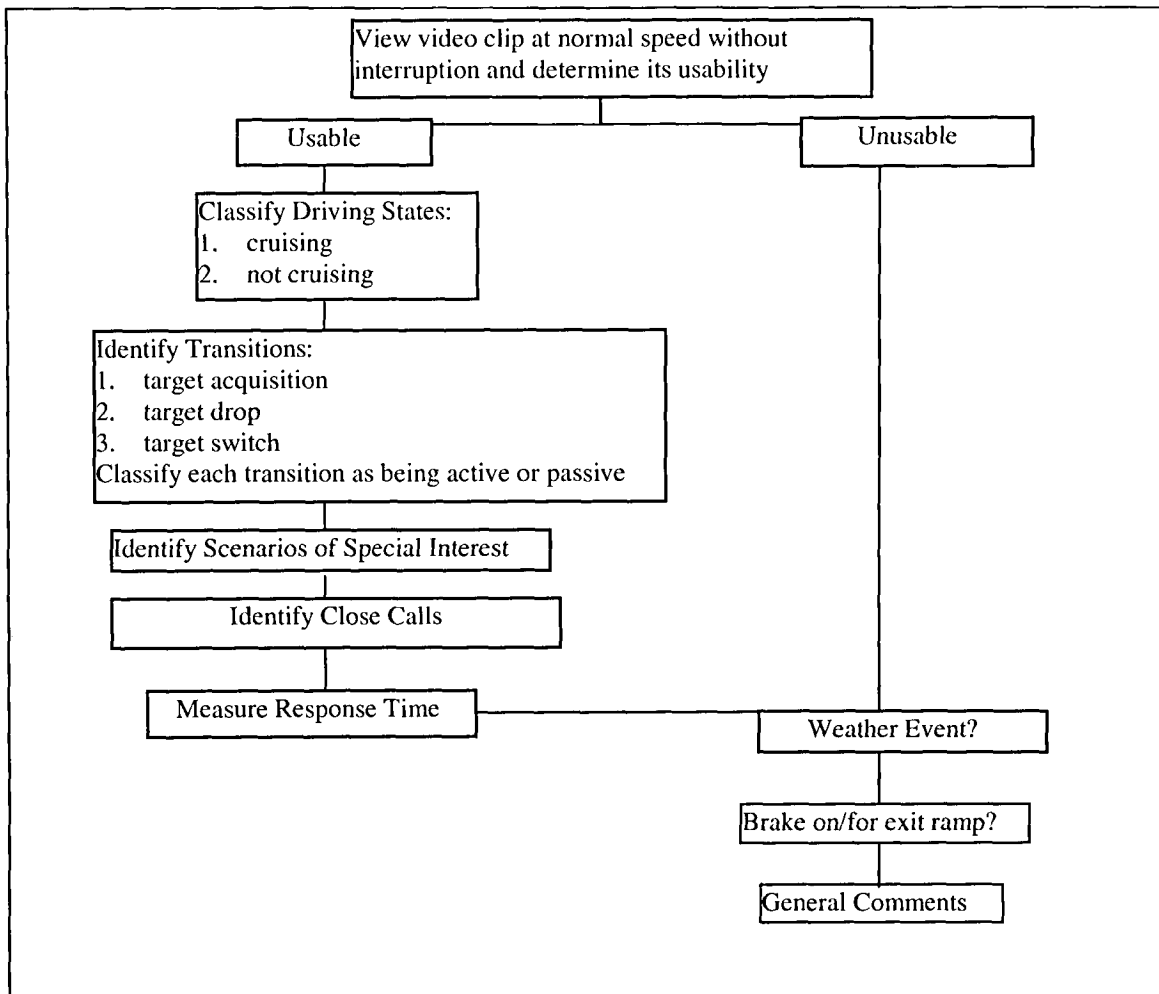
Figure 2. Sample Exposure Screen.

### Close Calls

One of the primary areas of interest in the video analysis is the occurrence, severity and proximity of close calls. If the analyst determines that the video clip was triggered (brake intervention, near encounter, concern) due to a potential interaction with another vehicle or object, or a near run-off the road event, then the “close call” button is selected. Figure 4 provides an outline of the procedure for identifying close calls and assigning severity and proximity values to them.

Once the “close call” button has been selected, a screen comes up that allows the analyst to identify the type of close call and proximity of the close call event.

This identification is performed using the on-screen Close Call Event Tree. (For description see reference for ICC Field Operational Test Video Classification Training Manual.) The analyst must move through the tree until the appropriate description of the close call is found. Upon selecting the appropriate close call description, severity is automatically assigned by the interface and displayed on the screen. The severity assigned is a function of the vehicle speed. This severity measure is the potential severity in the event of a crash. The severity values range from 1 to 4, where 1 is minor, 2 is marginal, 3 is critical and 4 is catastrophic. Proximity is a subjective measure of “how close” the close call event was to a crash. The analyst assigns the proximity rating



**Figure 3. Video Data Classification Protocol.**

according to the following scale (McGehee, 1996):

- Near miss - The driver is required to take immediate evasive action in order to prevent a crash.
- Hazard Present - The close call occurs when an object is present in the environment - requires that the object is in close enough proximity to represent a hazard to the ICC vehicle, but not close enough that an immediate evasive action must be taken to avoid it.
- No Hazard Present - The close call occurs when no close proximity obstacle is present in the environment.

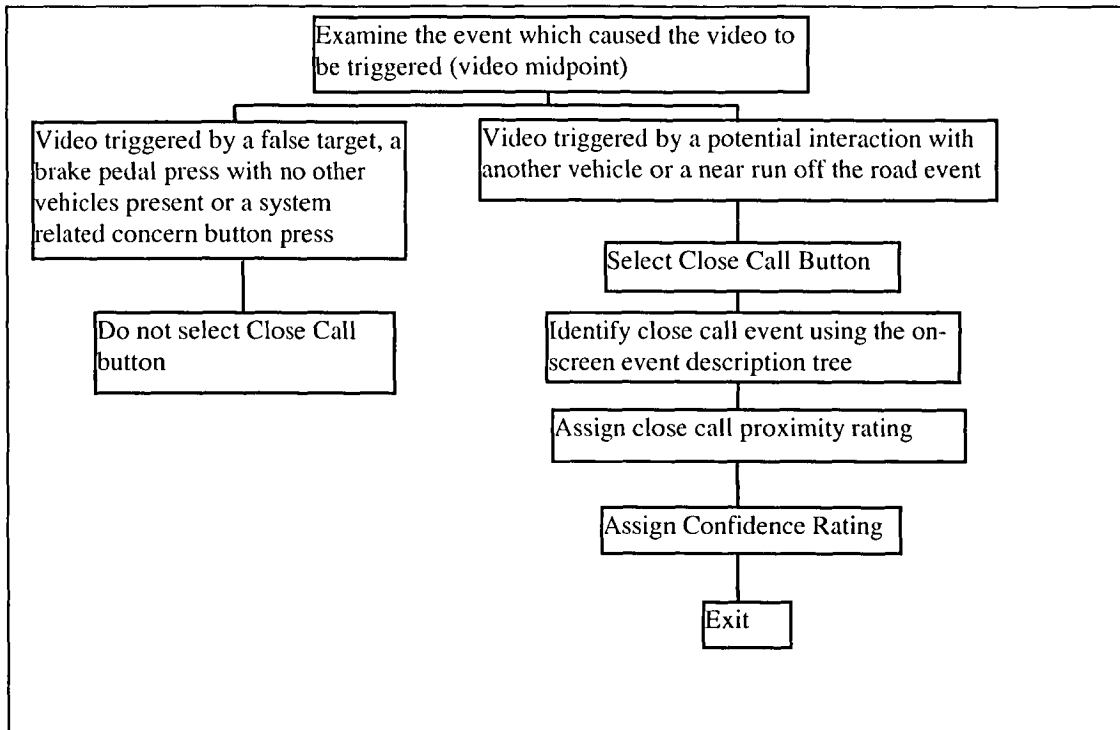
Proximity is assigned by selecting the appropriate proximity button on the close call screen.

### Driver Response Times

Another primary area of interest in the video analysis is the measurement of driver response times. Response

times are measured for events in which there is a measurable stimulus that generates a measurable response from the driver of the ICC vehicle. The response time is recorded by pressing a series of buttons to time stamp the stimulus and response and to record the time once the analyst is confident that he/she has accurately captured the event. In recording a response time, appropriate stimulus and response descriptions must be selected. Choices for the stimulus include:

- lead vehicle brake lights come on (visual);
- lead vehicle deceleration with no brake light (marked decrease in  $V_p$ );
- obstacle appears suddenly in ICC vehicle's path;
- cut-in where slower vehicle crosses lane line into ICC vehicle's lane; and
- other.



**Figure 4. Close Call Classification Procedure.**

If “OTHER” is selected, the analyst is required to provide a short description of the stimulus. Choices for the response include:

- ICC driver presses the brake pedal (brake variable goes from gray to blue);
- marked deceleration begins (noticeable decrease in V), or throttle off (1 to 0);
- start of lateral maneuver, e.g., driver swerves; and
- other.

Again, choice of the “OTHER” category requires inclusion of a text description of the response type. The video analyzer may record more than one response time for a given event since different combinations of stimuli and responses can occur.

### **Weather**

One of the final steps in episode video classification is to determine whether or not the video displayed events of precipitation or road spray. If rain, snow, or road spray was visible during the clip then the analyst marks the clip as a weather event. It is valuable to tag these events as they can result in inaccurate data being recorded.

### **Brake On/For Exit Ramp**

For video clips triggered by a brake intervention, the analyst is required to input whether or not the video was

triggered by a brake on, or for an exit ramp. If the video was triggered when the ICC driver pressed the brakes to slow down in the deceleration lane of a exit ramp, or when he/she pressed the brakes while on the exit ramp, then the analyst tags the event as a brake on/for exit ramp. This information will allow the evaluation team to estimate what proportion of triggered events were of this type, and may provide insight into other potential trigger alternatives for future applications.

### **CLASSIFICATION – EXPOSURE VIDEO CLIPS**

The general procedure followed by the video analyst in classifying an exposure video clip involves viewing the video clip and identifying the road class, the traffic density and whether or not the video clip shows evidence of precipitation or road spray.

With respect to road class, the analyst may choose between freeway, arterial, ramp and unusable. The unusable category is for video clips which show scenes of parking lots, driveways or other unusable scenes.

With respect to traffic density, the analyst may choose between none, light, moderate, heavy and congested. These categories correspond to levels of service (LOS) defined and depicted in TRB Highway Capacity Manual, 1994. This classification is intended as an informed estimate of congestion seen by the driver.

Identifying weather events in the exposure video clips serves the same purpose as identifying them in the episode

video clips. It is valuable to tag these events as they can result in inaccurate data being recorded.

## PRELIMINARY RESULTS

At the time this paper was prepared, video analysis on all 108 FOT subjects was not yet completed. Once the video analysis is completed and linked to the on-line numerical data base being developed by the evaluation team, interesting comparisons of event occurrences and driver behavior with and without ICC will be possible. So far, for 77 drivers, the video analyst has recorded:

- 4420 intervals cruising, 5893 not-cruising (7272 episodes);
- 5310 driving state transitions;
- 4606 close calls; and
- 866 driver responses.

Contingency (probability) tables of the driving state transitions, close calls, and response times are provided in Tables 1, 2 and 3, respectively.

**Table 1.**  
**Driving State Transitions - 77 Drivers**

	transitions			total
	target acquisition	target drop	target switch	
active	0.052	0.194	0.316	0.562
passive	0.079	0.103	0.255	0.438
total	0.131	0.297	0.571	1.000

**Table 2.**  
**Close Calls - 77 Drivers**

severity	proximity			total
	no hazard present	hazard present	near miss	
minor	0.002	0.002	0.001	0.005
marginal	0.000	0.011	0.000	0.011
critical	0.003	0.818	0.006	0.827
catastrophic	0.002	0.153	0.002	0.157
total	0.007	0.984	0.009	1.000

**Table 3.**  
**Driver Responses - 77 Drivers**

stimulus	response				Total
	Brake	Throttle Off	Lateral Maneuver	Other	
Brake Lights	0.784	0.140	0.002	0.000	0.926
Deceleration - No Brake	0.002	0.000	0.000	0.000	0.002
Obstacle	0.000	0.000	0.000	0.000	0.000
Cut-in	0.012	0.006	0.001	0.000	0.018
Other	0.036	0.015	0.002	0.000	0.053
Total	0.834	0.161	0.006	0.000	1.000

## OTHER POTENTIAL APPLICATIONS

The video analyzer has many potential extended applications. Three of these potential applications that are of particular interest to the evaluation team are introduced in the subsections below.

## Identification of Potentially Critical Scenarios

Because video clips may visually identify major event types not necessarily tagged in the primary data stream, further classifications are possible beyond those currently automated. An example already tried is the classification of braking and near encounter episodes by distribution of magnitude of the triggering event. For one driver, 146 episode clips were reviewed for levels of deceleration achieved by braking or deceleration demanded by a near encounter. These episodes were sorted into histograms for each type of triggering event, with counts of occurrences in bins spanning associated levels of deceleration. The shape of the histogram provides a basis for the determination and selection of specific cases for detailed examination. The research objective here is to capture and analyze similar "high g" scenarios by scenario type for ICC vs. non-ICC driving.

## Data Visualization

As data bases become larger and more complex, means that allow data visualization become very useful. The video analyzer allows visualization of several single and multi-dimensional data plots, synchronized with a visual record of what is actually occurring. This ability allows trends and relationships in and between data to be explored, and also allows study of data quality, consistency and accuracy.

## Application to Other FOT Data

While the video analyzer was developed specifically for classifying, analyzing and exploring data collected for the ICC FOT, it can be relatively easily altered to handle data collected in other ITS FOTs. In addition to allowing collection of required measures and classification information, the application of the video analyzer was extremely helpful to the evaluation in examining data trends, data quality, data consistency and data accuracy. The video analyzer also provided a test bed for testing and validation of the other classification tools developed for the FOT evaluation. The video analyzer could easily serve a similar role in the evaluation of data collected in another ITS FOT or related area of study, e.g. rear end crashworthiness.

## CONCLUSIONS

The ICC evaluation prompted the development of a video analyzer that allows video data to be easily classified for analysis. The video analyzer allows both video and plotted numerical data to be used in the data classification. The display of recorded numeric variables

also aids in comparing how the system sees the world vs. how the driver sees the world and allows study of data quality, consistency and accuracy.

The video analyzer has many potential extended uses. Several of these extended uses include identification of potentially critical scenarios, data visualization, and integration of video and digital data from sources other than the ICC FOT.

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# HEADLAMP PERFORMANCE IN TRAFFIC SITUATION

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## ABSTRACT

The photometric requirements of today's headlamps do not relate to the headlights as built into the vehicle, but to the individual headlamp before its installation. The aim of this survey is to demonstrate the relation between technical requirements of individual headlamps and the actual situation on the road. For that purpose headlamps were measured: on the one hand those of known vehicles (reference vehicles) with correctly adjusted and cleaned headlamps; on the other hand headlamps in everyday traffic, i. e. possibly incorrectly adjusted and soiled.

It could be shown that the glare of illuminance of the gas discharging headlamps in the measuring point of the human eyes of an on-coming car is lower than of normal traffic vehicles.

## INTRODUCTION

The legal requirements of headlamps vary from country to country. These regulations relate to the place, levelling and photometry.

## MEASURING

The measuring can be divided into the following items:

- Photometric measuring points (ECE and MVSS / SAE)
- Dynamic courses of the photometrics measuring points
- Dry road
  - Situation:
    - Humid
    - Rain
- Wet road
  - Situation:
    - Humid
    - Rain
- Reference vehicles
- Normal traffic

All in all twelve combinations are possible. The measuring points are shown in Figure 1 and Table 1.

**Table 1.**  
**Measuring Geometry.**

Measuring Geometry		
Measuring Point	Measuring Distance d / m	Position
50L	50.4	left road side
VL	50.4	left shoulder 1m left 2.50 m height
50R	50.4	right road side
VR	50.4	right shoulder 1m right 2.50 m height
75R	75.1	right road side
B50L	75.1	Direction as defined by relevant regulations
HV	95.4	Direction as defined by relevant regulations

## Street Geometry

The measuring equipment was set up on a "Bundesstraße" with a speed limit of 44 mph. The drivers were not informed about the measuring taking place.

## Photometric Measuring

The photometric measurements were made by single (V( $\lambda$ )-adapted) photoelements in the directions and distances as listed in Table 1. All values described later are recalculated for a distance of  $d = 25\text{m}$  and valid for a light distribution of a system with two superimposed headlamps. The possible forward reflection on the pavement into the direction of the photoelements was shielded. The whole measuring system was controlled by a system-timer of the computer used for the data collection.

## Photometric Requirements

For the measurements a set of measuring directions as listed in Table 1 and shown in Figure 1 were selected. The new measuring points VR and VL describe the situation of the illumination at traffic signing. The photometric limiting values except those for VR and VL



can be taken from the relevant ECE-Regulation. The photometric requirements for headlamps are based on certain test voltages. These voltages can differ from those measured at the headlamp mounted on a car. There are many other effects influencing the photometric values of headlamps for example

- ageing of headlamps and lenses
- ageing of filament lamps
- changing of the plugs' resistance, etc.

Therefore, a large variety of measured values could be expected.

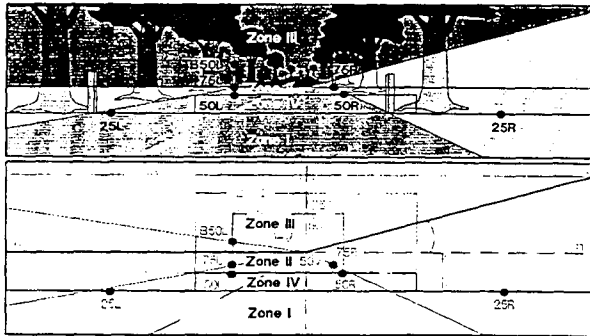


Figure 1. Measuring Points in Street Geometry.

## RESULTS

The speed of the vehicles varied from 40 to 48 mph (reference vehicles) and from 44 to 68 mph (normal traffic).

The results are split into four items:

Vehicles

- in normal traffic
- with gas discharging headlamps
- with H4-Headlamps
- with modular build up illumination

### Situation on the road (normal traffic)

In Figure 2 the illumination  $E(HV)$  of vehicles in normal traffic are shown.  $\bar{E}$  describes the arithmetic mean value.

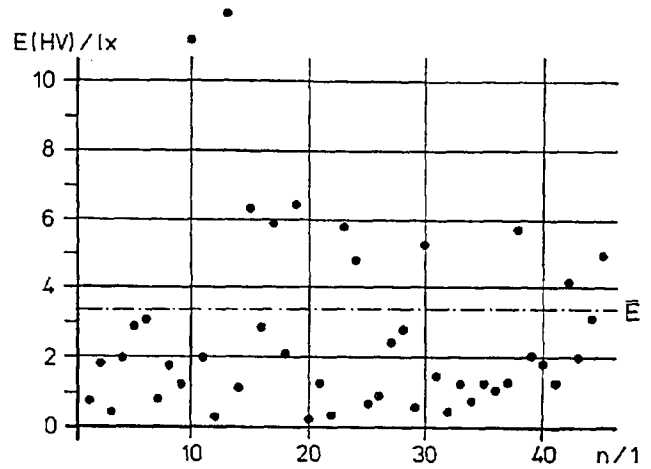


Figure 2. Illumination  $E(HV)$  for Normal Traffic.  
Number of Measurements:  $n = 78$

The figure illustrates the great variety of results in the HV-point. The mean value  $\bar{E}$  follows after measuring pairs of headlamps in normal traffic. The values' scattering results from a high gradient in the HV-point, incorrectly adjusted and/or soiled headlamps. The single headlamp's mean value exceeds the legal maximum value of the ECE regulation which amounts to  $E = 0.7$  lx. Apart from the already mentioned reasons, the high voltage in the vehicle and its variation (mean value 13.5 V instead of the supposed 12 V) are responsible for this effect.

Figures 3 and 4 show the frequency distribution  $f$  of the  $E(B50L)$  and  $E(75R)$ . A normal distribution ensues from both diagrams. The mean values amount to

$$E(B50L) \approx 1.04 \text{ lx and}$$

$$E(75R) \approx 10.3 \text{ lx.}$$

While the glare point of B50L surpasses the legal standard of 0.4 lx (per individual headlamp) only slightly, the minimum value of 12 lx in 75R is not achieved by far. Consequently, the distance of recognition is shortened and this results in a decrease of safety in traffic.

The measurements were repeated on several days during like weather conditions. Figure 5 plots the mean values of four sensors during six/seven different measurements in normal traffic. Every sketched value is based on a minimum of 33 and a maximum of 406 different vehicles. The discrepancies, which become particularly visible in the HV-value, again refer to insufficiently adjusted and soiled headlights.

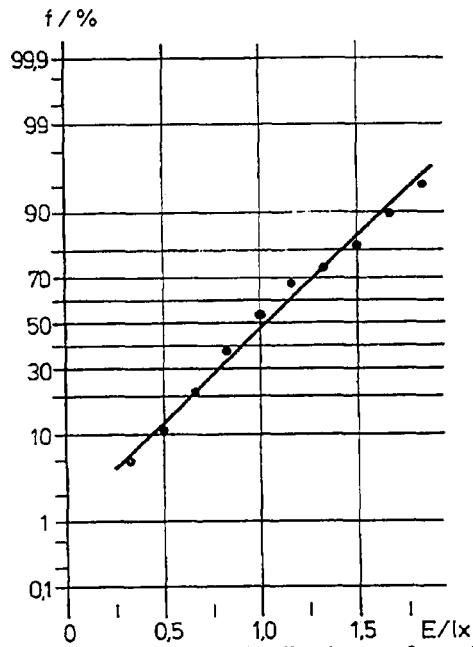


Figure 3. Frequency Distribution  $f$  of the Illumination  $E(B50L)$  for Normal Traffic. Number of Measurements:  $n = 78$

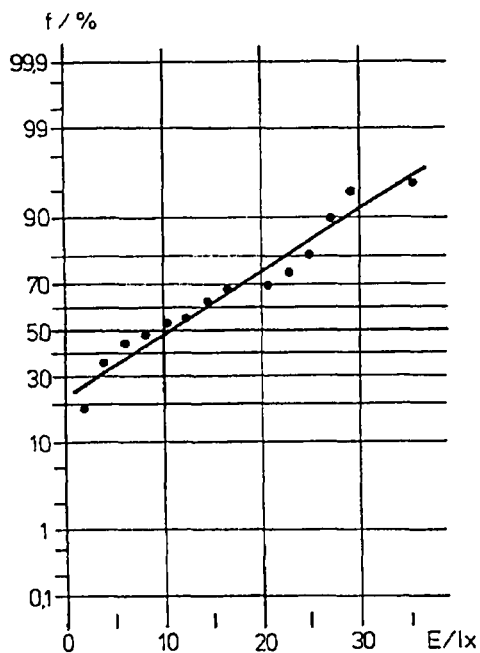


Figure 4. Frequency Distribution  $f$  of the Illumination  $E(75R)$  for Normal Traffic. Number of Measurements:  $n = 78$

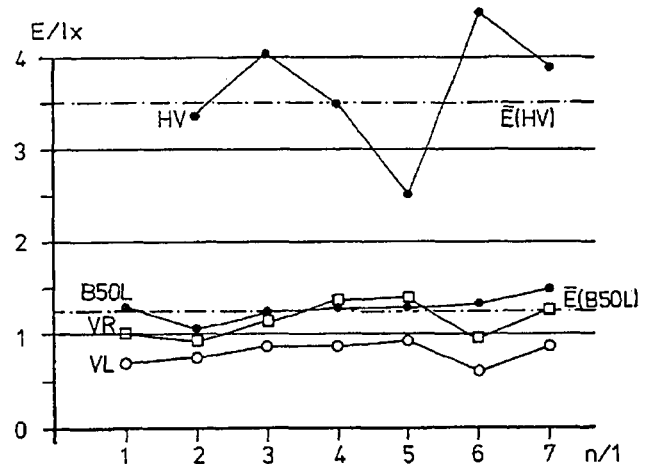


Figure 5. Mean Values of the Illumination  $E$  for Different Measurement Series  $n$ .

HV, B50L: Illumination in the Measuring Direction HV, B50L

VR, VL: Illumination in the Measuring Direction of Shoulder Mounted Traffic Signs (R: Right Shoulder, L: Left Shoulder)

$\bar{E}(HV)$ ,  $\bar{E}(B50L)$ : Calculated Mean Values

The relation between  $E(B50L)$  and  $E(75R)$  is shown in figure 6. The mean values of the glare-point and the range amount to 1.06 lx and 12.3 lx respectively. As a conclusion follows:

$$\frac{\bar{E}(B50L)}{\bar{E}(75R)} = \frac{1}{10}$$

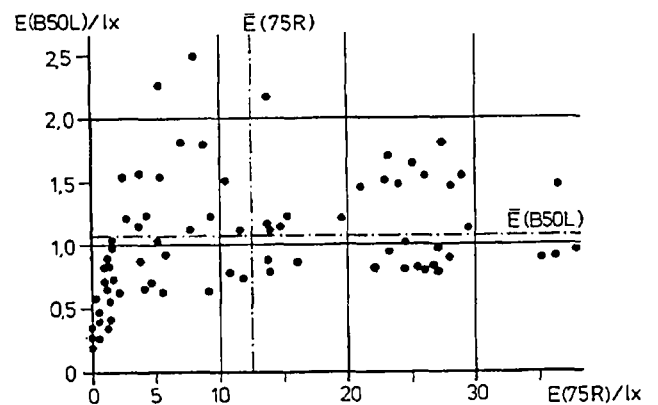


Figure 6. Illumination  $E(B50L)$  and  $E(75R)$  for Normal Traffic.

$\bar{E}(HV)$ ,  $\bar{E}(B50L)$ : Calculated Mean Values  
Number of Measurements:  $n = 78$

## Gas Discharge Headlamps (GDL)

During the last years the glare of headlights with GDLs has been discussed. The road users' subjective judgements usually declare them as being more glaring than those headlamps common up to now. Because of that, vehicles with these light sources were separately analysed so that an objective conclusion could be drawn. Figures 7 and 8 depict the luminous flux of a vehicle with correctly adjusted headlights in the points of B50L and 75R. The mean values amount to  $\bar{E} \approx 1.1$  lx and  $\bar{E} \approx 38$  lx respectively and fulfil the legal requirements. The glare values do not exceed those in normal traffic, that is to say, those of vehicles with conventional halogen headlamps.

$E(B50L) / \text{lx}$

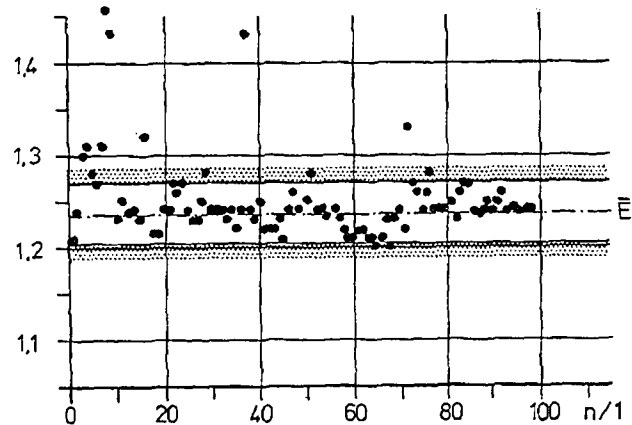


Figure 7. Illumination  $E(B50L)$  for Single Measuring for One Car with Gas Discharge Headlamps.  
 $\bar{E}$ : Calculated Mean Value for  $E(B50L)$   
 Number of Measurements:  $n = 95$

$E(75R) / \text{lx}$

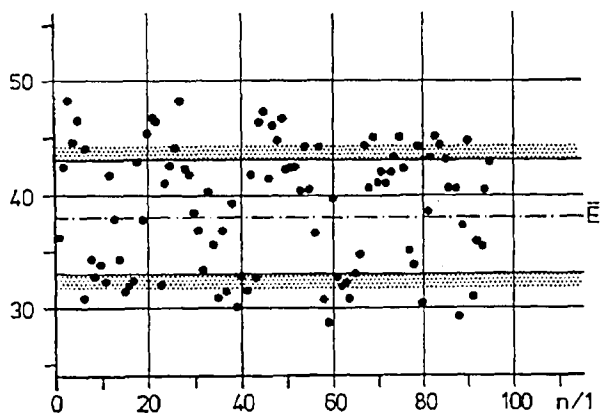


Figure 8. Illumination  $E(75R)$  for Single Measuring for One Car with GDL-Headlamps.  
 $\bar{E}$ : Calculated Mean Value for  $E(75R)$   
 Number of Measurements:  $n = 95$

The GDL's relation of glare and range, however, comes up to about 1:30 and reaches a value three times as high as the one measured during normal traffic. An intensified use of GD-Headlamps would therefore contribute to the enhancement of vehicle safety.

For reference measurements and the comparison of knowingly correctly adjusted and clean headlamps with those of normal traffic, eleven different vehicles were employed and taken into account. 10 to 87 times each of these were driven along the measuring range, which resulted in 358 individual measurements. In Figure 9 the measuring point B50L of correctly adjusted and clean headlamps as well as the values gained during normal traffic are plotted. It shows that the glare values in the second survey of identified headlamps are in most cases lower.

$E(B50L) / \text{lx}$

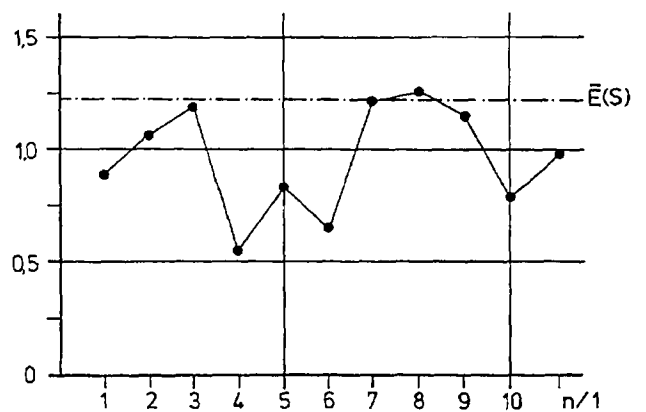


Figure 9. Mean Values of the Illumination  $E(B50L)$  for Single Cars.  
 $\bar{E}(S)$ : Calculated Mean Value for  $E(B50L)$  for Normal Traffic  
 Number of Measurements:  $n = 10 \dots 87$

A comparison of glare and range in Figure 10 reveals that its relation comes up to 1:50 in the case of correctly adjusted and clean headlamps. Due to these results, enhanced vehicle and traffic safety could be achieved by further use of headlamp washers as well as by ensuring that headlights will correctly be adjusted.

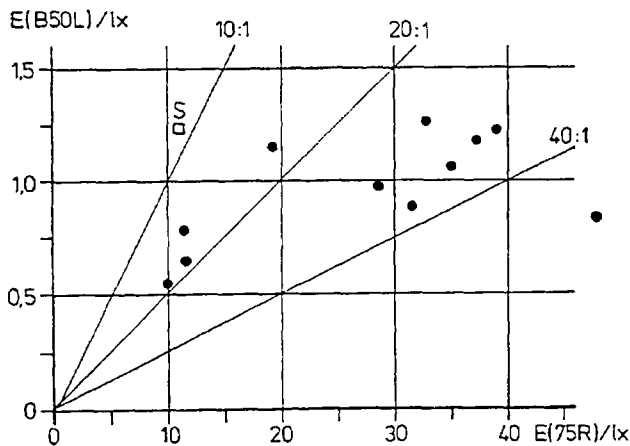


Figure 10. Mean Values of the Illumination  $E(B50L)$  and  $E(75R)$  for Different Types of Headlamps.

Number of Measurements:  $n = 95$   
 S: Calculated Mean Value During Normal Traffic

#### Comparison of Various Tests

The comparison of various headlamps in different measuring points on dry road is plotted in Figures 11 and 12. The following categories of vehicles are shown:

- normal traffic ( $n=363$ )
- individual vehicles with GDLs ( $n=82$ )
- individual vehicles with H4-headlamps ( $n=97$ )

The mean values are plotted logarithmically.

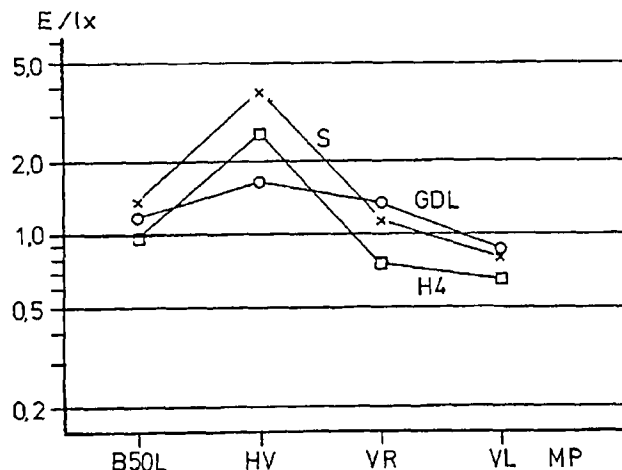


Figure 11. Mean Values of the Illumination  $E$  in Different Measuring Directions for Cars with Different Headlamps.

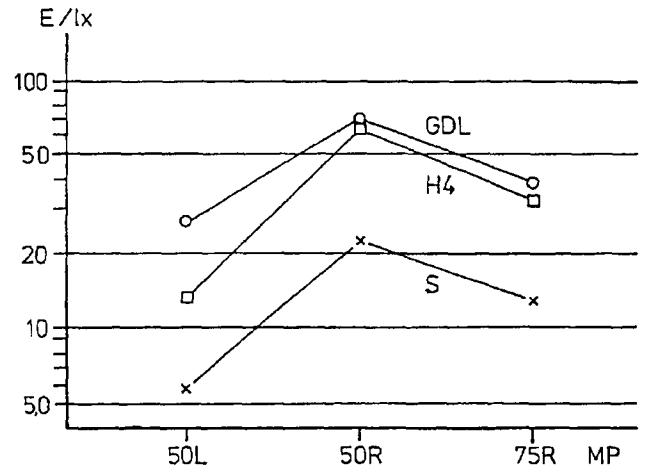


Figure 12. Mean Values of the Illumination  $E$  in Different Measuring Directions for Cars with Different Headlamps.

A comparison of the measured values demonstrates that the illumination of the GD-headlamps is better than any other, i. e. the glare value is lower and the other measured values higher than those of the other categories. (Only in B50L almost all headlamps show the same value of the luminous flux). Once again, it can be ascertained that the GD-headlamps could provide for an enhancement of vehicle safety.

#### Adverse Weather Condition

The tests on dry road excluded the measuring of the forward reflection. On humid or wet road that kind of reflection accounts for a significant share in the measuring points – especially in the glare-point B50L. Due to this fact, the set-up was modified for these tests. The changes of the measured values can be seen in the Figures 13 and 14.

The periods of rain are divided into three phases:

Table 2:  
Comparison of  $E(B50L)$  on Dry and Wet Road

from n	to n	Rain	$\bar{E}_d/\bar{E}_w$	
			H4	GDL
1	18	Heavy	1:10	1:9
19	50	Normal	1:2.5	1:2
51	70	Medium*	1:7	1:6

\*dry road conditions

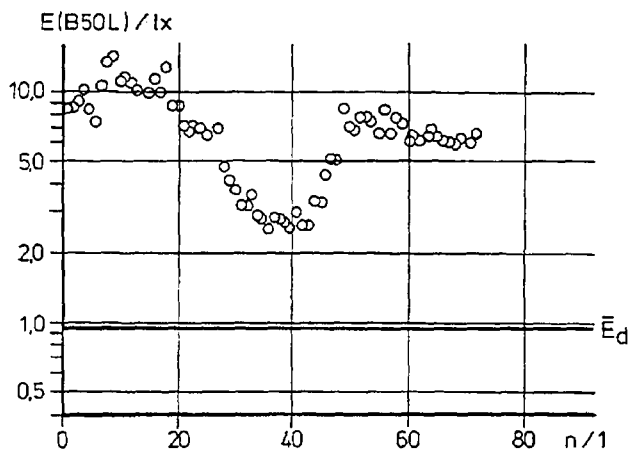


Figure 13. Variation of the Illumination  $E(B50L)$  of H4-Headlamps of Single Car During a Rainfall Period.

$\bar{E}_d$ : Calculated Mean Value for  $E(B50L)$   
Under Dry Weather Conditions  
Number of Measurements:  $n = 71$

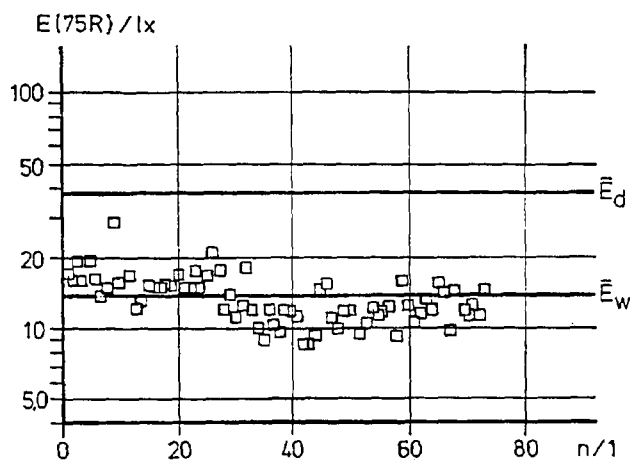


Figure 14. Variation of the Illumination  $E(75R)$  of GDL-Headlamps of Single Car During a Rainfall Period.

$\bar{E}_d$ : Calculated Mean Value for  $E(75R)$   
Under Dry Weather Conditions  
 $\bar{E}_w$ : Calculated Mean Value for  $E(75R)$   
Under Wet Weather Conditions  
Number of Measurements:  $n = 71$

During the different intensities of rain, varying degrees of increased luminous flux in the glare-point can be observed (cf. Table 2). By contrast, the luminous flux in 75R are similarly high as the values on dry road.

The results gained of the vehicles in normal traffic appear to be more randomly distributed. An increase in the luminance in B50L, however, can be perceived, which amounts to the factor 1:3.

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# THE REQUIREMENTS FOR DRIVER ASSISTANCE SYSTEMS AND THEIR EFFECTS ON REAL-LIFE ACCIDENTS

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## ABSTRACT

The development of electronic systems in cars is strongly increasing and especially driver assistance systems will be available in a short time. Therefore their effectiveness in accident avoidance related to defined critical situations and their influence on driver behaviour has to be analysed.

On the basis of the GDV large scale accident material an assessment has been made which part of car crashes with personal injury could be influenced by driver assistant systems. This paper presents the results of the first research phase.

## INTRODUCTION

In the past few decades, great success has been achieved in Europe in the field of traffic safety. Without it, the number of road casualties and follow-up costs would be much greater today. In the last few years, developments aimed at improving both traffic flow and traffic safety have concentrated on collective information and guide systems. In the area of automotive engineering in particular, passive vehicle safety has been improved.

Accompanied by the rapid development of microelectronics, individual information and control systems are gaining in importance. They are usually linked to one particular

vehicle and assist the driver in complex motoring situations which are objectively difficult to assess, perhaps even critical. They are intended to ensure that the constant increase in traffic volume is dealt with in a safe and efficient manner within an infrastructure that is only capable of limited expansion and development.

The present paper is devoted to driver assistance systems and their contribution to traffic safety. It concentrates in particular on the system of adaptive cruise control (ACC) which is intended to increase vehicle comfort and to reduce the number of rear-end accidents (REA). The example of rear-end accidents is used to illustrate the general requirements that an adaptive cruise control system must fulfill in order to function properly, i.e. prevent accidents.

The accident data used in this paper originates from real traffic accidents in Germany which have been documented by records and protocols from the police, third party insurance companies, district attorneys and public prosecutors, by photographs, expert opinions and witness testimony. Two GDV accident databases were used which were created in connection with a representative survey of vehicle safety /1/ and of autobahn accidents resulting in death /2/. These statistics comprise a total of more than 7000 rear-end accidents – all of them involving personal injury. These statistics have been

evaluated several times by different authors, refer in this context to the bibliography. In addition, the results of the official accident statistics for Germany, which are published annually, have been used to supplement the above material /3/.

Adaptive cruise control is a radar-assisted system designed to regulate the spacing between the driver's own car and a vehicle in front of it (Figure 1). The system recognizes the vehicles in front and regulates the speed of the driver's car whenever the driver's car fails to maintain a calculated safety margin. The safety margin is calculated taking weather conditions, road conditions and speed into account. The safety margin is adjusted on the basis of a braking

deceleration that does not exceed a maximum of  $2 \text{ m/s}^2$ .

The stage of development (stage 1) now achieved by the adaptive cruise control system recognizes vehicles in front that are traveling at a speed of at least 40 km/h. Slowly moving vehicles, turning and stationary vehicles are not identified, nor are pedestrians, cyclists and objects at the roadside. Test series and field tests using ACC prototypes installed in standard cars are currently being conducted in Germany. The development of driver assistance systems is intended to enhance both individual motor-ing comfort as well as general traffic safety at one and the same time.

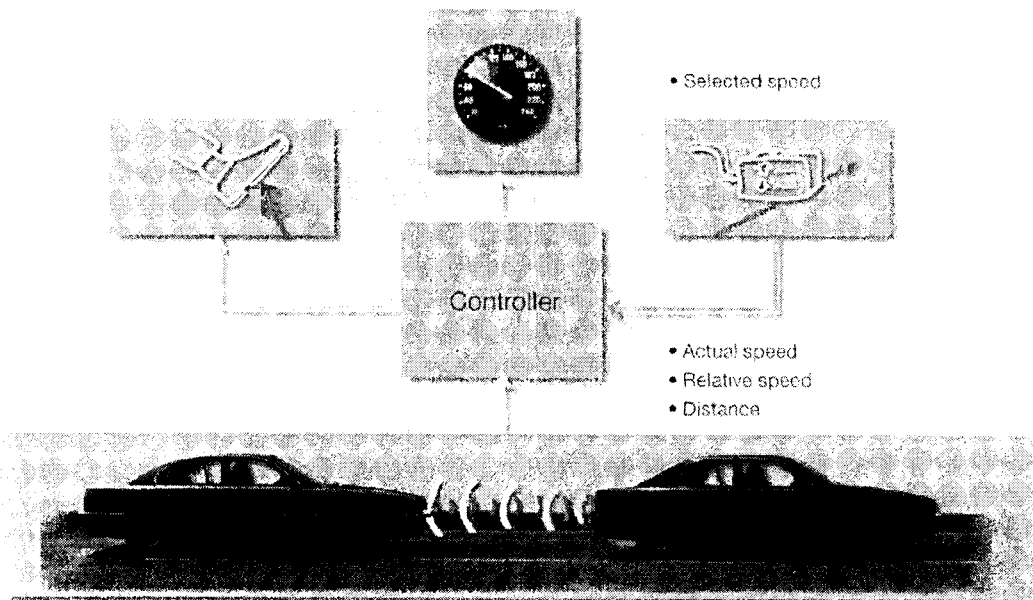


Figure 1. Adaptive cruise control – main components (BMW AG, 1996)

## TRAFFIC ACCIDENTS IN GERMANY

**General results** - There were approximately 50 million motor vehicles on the roads in 1995, of which approximately 41 million were automobiles. The annual distance traveled by all motor vehicles totaled 603.5 billion kilometers, 180.9 billion km (30 %) of which on German highways (the autobahn). Police authorities registered a total of 2.27 million traffic accidents nationwide in 1996, of which 1.90 million ac-

cidents involved only material damage and 0.37 million personal injury.

The official accident statistics /3/ reveal the following events which, generally speaking, lead or have led to accidents (all types of accidents). These statistics also apply to rear-end collisions as well in the broader sense of the word.

- Young persons between 18-25 years of age are by far the most endangered motorists. Based on a population of 100,000, this age group have accidents

approximately three times more frequently than subsequent age groups.

- About double as many men are involved in car accidents than women (both as persons causing accidents as well as persons involved in accidents). In the age group of young drivers (18-25 years of age), men caused accidents in more than 70% of all cases.
- Based on total kilometers traveled, the number of persons involved in accidents has remained at the same level in the last few years, whereas the number of

fatalities and serious injuries has declined.

- An inadequate safety margin is cited with varying degree of frequency in police accident records as the main error committed by car drivers. The percentage of accidents involving personal injury on the German autobahn is 19 % and on country roads 8 %. As far as the age distribution is concerned, there is an accumulation among drivers 18-21 years old and among drivers 45 years old and older (Figure 2).

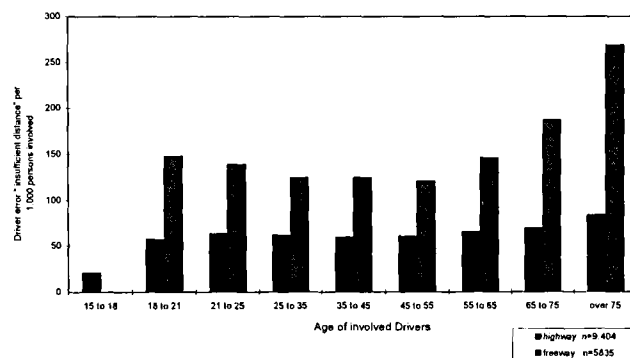


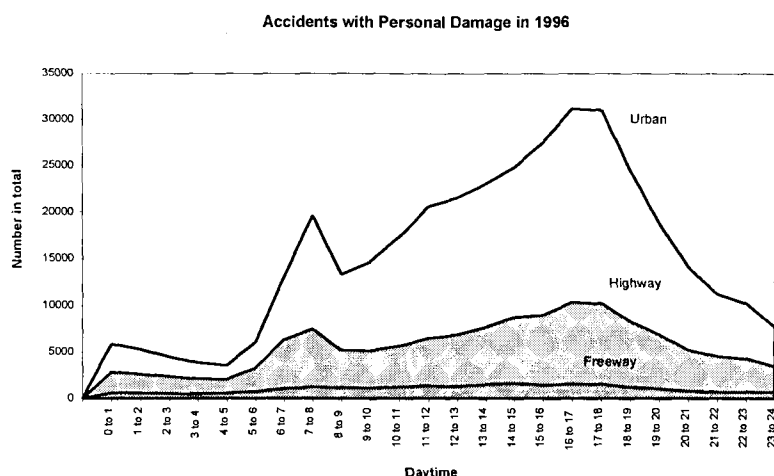
Figure 2. Drivers' error "inadequate safety margin" per 1,000 involved persons /3/

- Approximately 35 % of all autobahn accidents registered by the police occur in zones with speed limits ( $v = 60 - 130$  km/h) and 5 % in or near construction sites.
- As far as lighting conditions are concerned, 2/3 of all accidents involving personal injury occur during the day and 1/3 at night. These statistics are

equally applicable to country roads and the autobahn network.

- Approximately 0,5 % of all accidents involving personal injury outside of town (autobahn and country roads) were accidents that took place in fog.
- Less than 1 % of all accidents involving personal injury could be attributed to technical defects on the vehicle itself.





**Figure 3. Distribution of accidents involving personal injury over daytime**

**Rear-end accidents** - Rear-end accidents can be filtered out of the official accident statistics /3/ by breaking down traffic accidents according to the type of accident. Rear-end accidents belong either to accident type 1 (collision with another vehicle which starts, stops or is stationary in quiet traffic) or to accident type 2 (collision with another vehicle traveling in front or with a stationary vehicle).

According to the traffic conditions rear-end accidents are predominant among autobahn accidents (Table 1). Almost every other autobahn accident involving personal injury is a rear-end accident (46 %) and almost one out of every four accidents (21 %) is an accident involving serious material damage.

Of the total number of accidents that occurred in Germany in 1996, police registered

14,866 rear-end autobahn accidents, 11,363 of these involving personal injury,

and

20,553 rear-end accidents on country roads, 17,776 of these involving personal injury.

A total of 55,976 rear-end accidents involving personal injury occurred within city limits, thus accounting for 24 % of all accidents involving personal injury within city limits.

**Table 1-a**  
**Rear-end accidents involving serious material damage in 1996 according to location /3/**

Type of Accident	Urban		Country Roads		Autobahn		Total	
	abs.	%	abs.	%	abs.	%	abs.	%
Rear-end Accidents	9.379	14,5	2.777	7,4	3.503	20,6	15.659	13,1
Others	55.446	85,5	34.608	92,6	13.467	79,4	103.521	86,9
Total	64.825	100	37.385	100	16.970	100	119.180	100

**Table 1-b**  
**Rear-end accidents involving personal injury in 1996 according to location /3/**

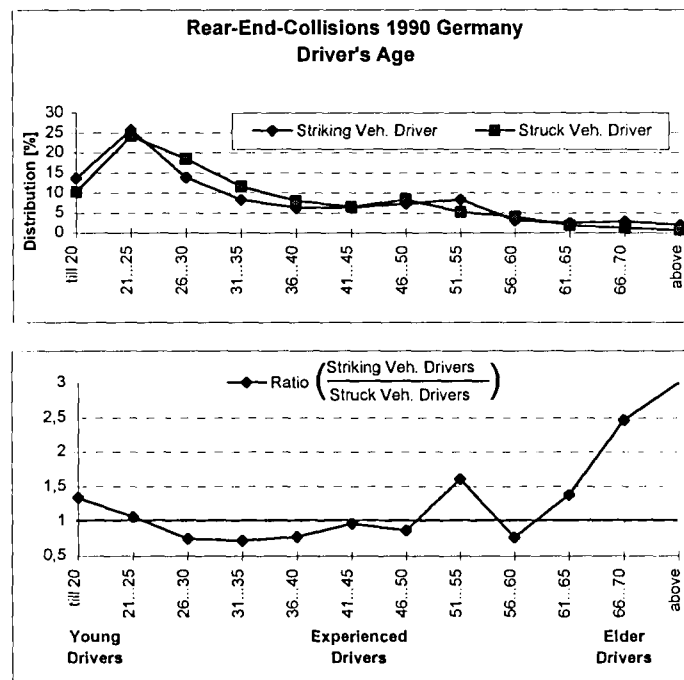
Type of Accident	Urban		Country roads		Autobahn		Total	
	abs.	%	abs.	%	abs.	%	abs.	%
Rear-end accidents	55.976	24	17.776	16	11.363	46	85.115	23
Others	180.033	76	94.321	84	13.613	54	287.967	77
Total	236.009	100	112.097	100	24.976	100	373.082	100

#### Analysis Of Rear-End Accidents

**Responsible vehicle drivers** - Men predominate the picture both in the case of rear-end accidents as well as in other types of accidents. Approximately 70 % of the persons causing rear-end accidents are men.

As far as the age distribution is concerned, drivers up to 30 years of age are the pre-

dominant factor in the case of rear-end accidents. They are responsible for almost 50 % of all persons involved in rear-end accidents. Based on the ratio of responsible drivers to participants, elderly drivers (60 years and older) are conspicuous in addition to young drivers up to 25 years of age (Figure 4).



**Figure 4. Driver's age in rear-end accidents in Germany**

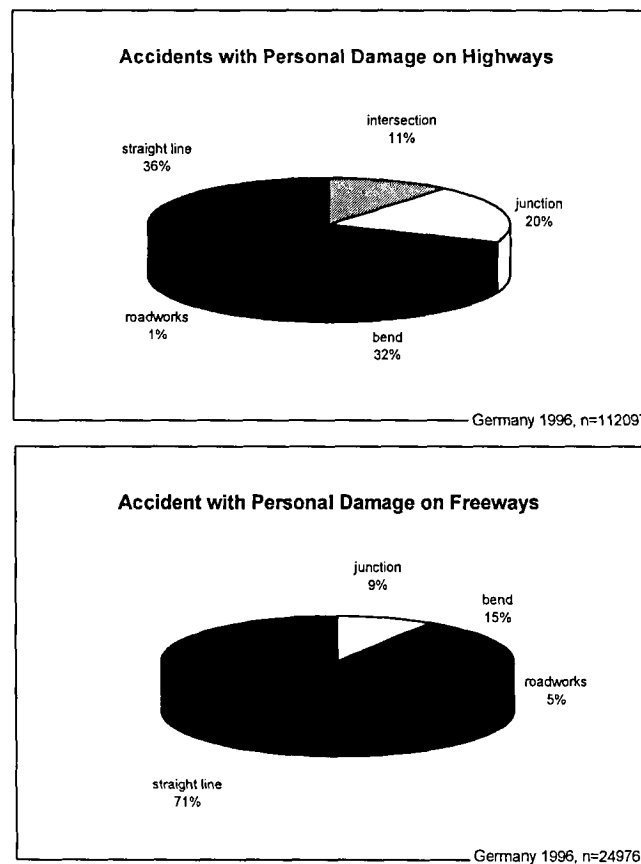
**Road category** - Based on known findings, severe rear-end accidents involving personal injury (refer to Table 1a) occur

- in 66 % of all cases on streets within city limits,
- in 21 % on country roads and
- in 13 % on the autobahn.

**Attendant circumstances** - The majority of rear-end autobahn accidents happen on straight sections of road (75 %), whereas curves and junctions are where most accidents occur on country roads (approx. 30 % in each case), refer to Figure 5.

As far as the light and road conditions are concerned, most rear-end accidents occur on dry pavement:

Pavement		Light	Percentage
dry	and	light	41 %
dry	and	dark	29 %
wet	and	light	14 %
wet	and	dark	16 %



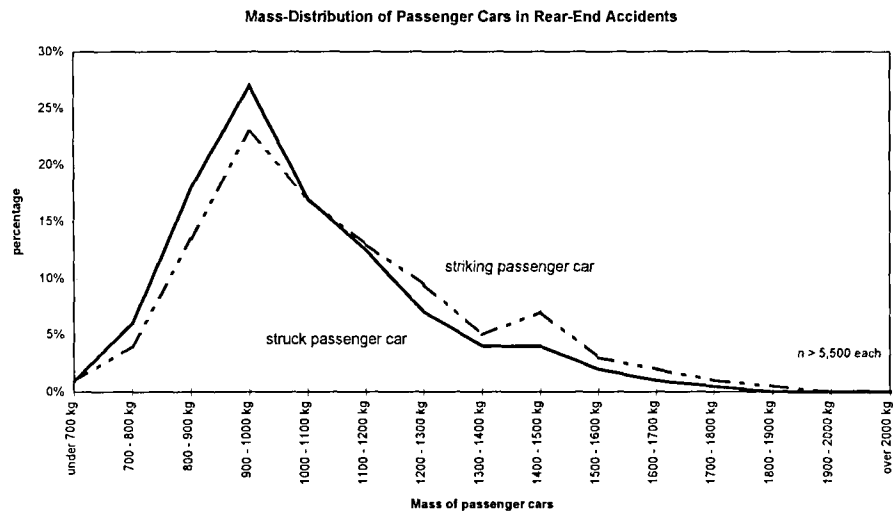
**Figure 5: Site of rear-end accidents /3/**

When the factors underlying the accident data were analyzed, there were no indications the conditions of light and pavement were significant, although visibility was classified into two categories: clear and obscured /4/.

**Involved vehicles** - The evaluation of the data has provided the following indications as far as the vehicles involved in two-car rear-end accidents are concerned:

- half of the vehicles involved had a vehicle weight of  $\leq 1000$  kg (Figure 6).

- smaller vehicles ( $\leq 1100$  kg vehicle weight,  $\leq 55$  kW engine rating) are more frequently the involved vehicle (the rear-ended vehicle) in their class; larger vehicles ( $\geq 1400$  kg vehicle weight,  $\geq 90$  kW engine rating) are more frequently the cause of the accident (the rear-ending vehicle).
- There are indications that older vehicles are more frequently the cause of the accident in their age class. The statistical data, however, does not allow reliable conclusions to be drawn (Figure 7).



**Figure 6. Passenger car mass distribution for rear-end accidents /5/**

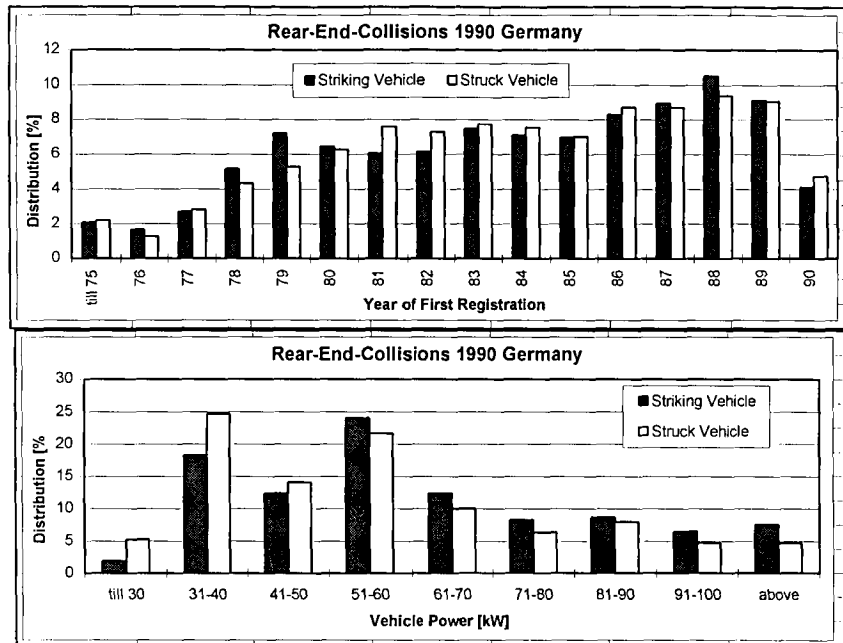


Figure 7. Passenger vehicles (model/year and power) involved in rear-end accidents (in Germany)

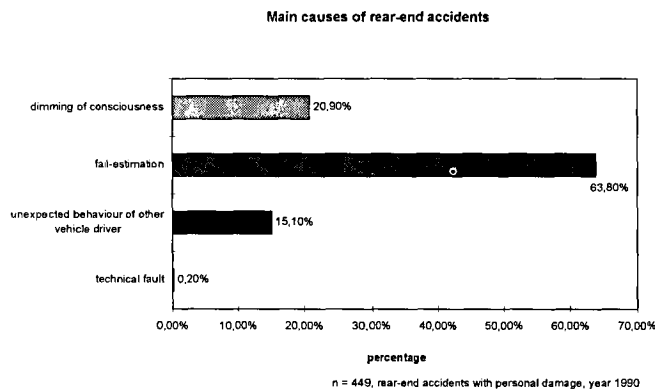


Figure 8: Main causes of rear-end accidents /5/

**Causes** - A random sampling of 520 rear-end accidents (two-car accidents involving personal injury) indicated the following main causes of accidents (Figure 8):

- Driver misjudgment 64.7 %
- Distraction/clouded awareness 20.9 %
- Unpredictable behavior 15.1 %
- Technical defects 0.2 %

The cases designated "driver misjudgment" means in the majority of cases that the driver "overlooked" the stopped or turning vehicle in front of his vehicle. In many

cases, a stationary vehicle was recognized, but only when it was already too late. There is not an insignificant number of cases in which drivers are distracted by an

accident, by tuning the radio or by children in the car. The unpredictable behavior of other motorists plays a causal role in 15 % of the rear-end accidents in this study. Technical defects are insignificant both here as well as in other types of accident.

Based on the known findings, it is obvious that rear-end accidents are caused for the most part by inattentiveness and are not due to external, unavoidable circumstances.

- $v \geq 40$  km/h
- $v \geq 80$  km/h
- $v \geq 100$  km/h

A comparison of driving speeds (Figure 9) reveals that in approximately half of all cases the differences amounted to between 20 and 40 km/h. The differences in speed are greater on country roads than on the autobahn /4/.

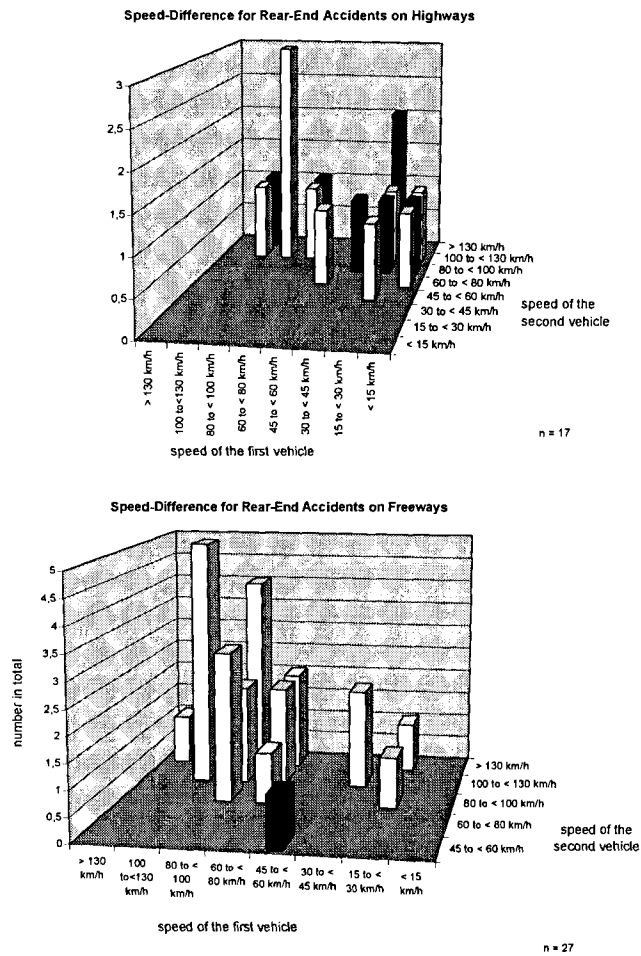
The deformations of the vehicles involved in rear-end accidents can be used to determine

When drawing up police reports about accidents, the police have attributed the error of inadequate safety margin to more and more young and elderly persons causing accidents, refer also to Figure 2.

**Driving and collision speed** - Statements about the speed of a vehicle prior to a two-car rear-end collision show that the person who rear-ends a vehicle ahead of him ( $v > 0$  km/h) was traveling at the following speeds prior to the accident:

- 100 %
- 80 %
- 60 %.

the difference in speed at the time of the collision  $v_{\text{coll}}/5/$ . Accordingly, the difference in collision speeds was less than 15 km/h in more than 70 % of 496 evaluated rear-end accidents.  $v_{\text{coll}}$  values greater than 25 km/h occurred in only 6 % of the cases analyzed (Figure 10).



**Figure 9. Driving speed differences of passenger cars involved in rear-end accidents on highways and autobahns /4/**

**Figure 10. Speed difference at the beginning of the crash phase for rear-end accidents of two passenger cars /5/**

**Rear-ending stationary and moving vehicles** - The number of stationary and moving vehicles involved in rear-end collisions (two-car accidents involving personal injury) are approximately the same. This ratio can be taken as an orientation value for all rear-end collisions irrespective of the location in which they occurred.

**Injuries** - Approximately half of all persons injured on the autobahn sustain their

injuries in rear-end collisions. In 1996 a total of 20,210 persons were injured during rear-end accidents on the autobahn, 316 of whom were killed and 3,330 of whom suffered serious injury. The number of casualties on country roads totals 27,011, of whom 190 were killed and 3,655 were seriously injured. Rear-end collisions thus result in about 16 % of all persons injured on country roads and 50 % of all persons injured on the autobahn (Table 2).

**Table 2:**  
**Motorists involved in rear-end accidents – 1996 /3/**

Motorists involved in accidents	Urban		Country roads		Autobahn		Total	
	abs.	% total	abs.	% total	abs.	% total	abs.	% total
Minor Injuries	66.838	28,5	23.166	20,8	16168	53,8	106.172	28,2
Severe Injuries	5.627	10,4	3.655	6,9	3.330	37,1	12.612	10,8
Killed	87	4,1	190	3,4	316	3,1	593	6,8
Involved Motorists	72.552	24,9	27.011	15,9	20.210	49,5	119.377	23,8
Rear-end Accidents	55.976	23,7	17.776	15,8	11363	45,6	85115	22,8

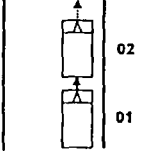
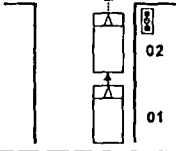
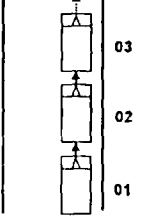
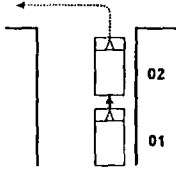
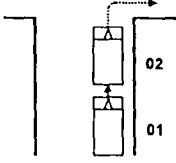
**Types of rear-end accidents** - Zierden /6/ analyzed 24 rear-end accidents and used this to derive a typology of rear-end accidents (Figure 11). The data material used (GDV, 1990) contains rear-end accidents

from all locations (city streets, county roads and the autobahn). The following were described as typical situations for rear-end accidents:

- |   |      |
|---|------|
| 1: rear-end accident along a straight road (2 or more persons involved) | 57%  |
| 2: rear-end accident in junctions (with/without traffic lights)         | 32 % |
| 3: rear-end accident in curves  | 11 % |

The number of rear-end accidents involving several persons is not insignificant /5, 9/.

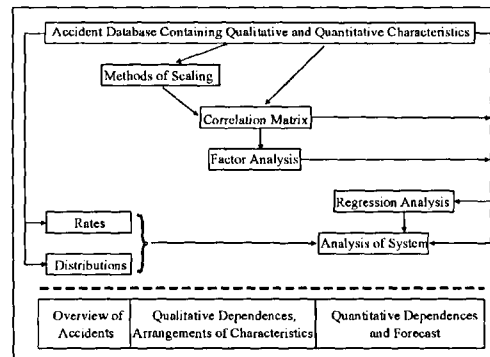


Auffahrunfalltyp (A)  48 %	
Auffahrunfalltyp (B)  14 %	
Auffahrunfalltyp (C)  9 %	
Auffahrunfalltyp (D)  9 %	
Auffahrunfalltyp (E)  8,6 %  (Sonstige 11, 4 %)	

**Figure 11. Types of rear-end accidents /6/**

**Factor Analysis** - A number of existing accident databases were used to evaluate parameters for the events leading up to an accident. One method is described below which was used to perform a complex system analysis of a database maintained by the German Insurance Association (GDV) con-

taining 15,000 two-car accidents involving personal injury. Figure 12 shows the mathematical-statistical methods that were used either individually or in the sequence given.



**Figure 12. Scheme of accident data analysis**

The calculation of frequencies and distributions provides an overview of the individual characteristics. The connections between the accident characteristics are reproduced by the correlation matrix. In order to calculate the correlation coefficients, it is advantageous to assign values to the expressions of the individual characteristics (clear, rain, snow, hail, etc. for the example of weather) when the quantitative characteristics are known (e.g. weather conditions, visibility, etc.). The scaling method according to Bargman/Schünemeyer (1989) was found to be suitable for this purpose.

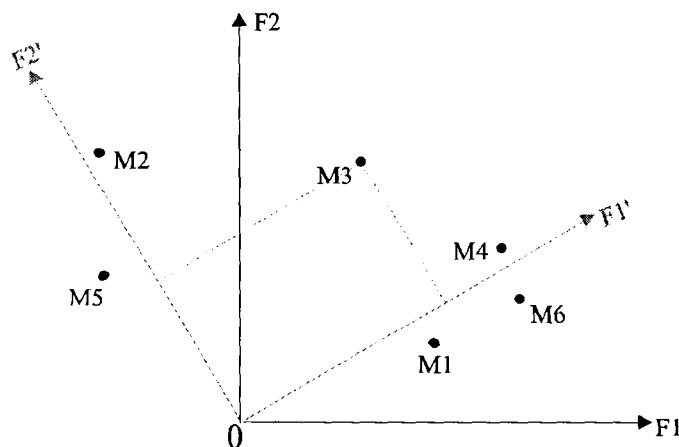
If there are many characteristics that describe the accident, the connections in the correlation matrix can no longer be interpreted. Factor analysis can then be used for the purpose of interpretation. The aim of factor analysis is to attribute the correlations between the characteristics to the action of common, linearly independent (fictive) factors. To do this, the individual characteristics are represented in a coordinate system based on the calculated correlation matrix in such a way that this reproduces the existing connections as best possible. The axes of the coordinate system are termed "factors". All characteristics are assigned "charges" with respect of each factor. These charges can be interpreted again as correlation coefficients. The difference between the original correlation coefficient and the correlation coefficient

reproduced by this procedure is termed the "residual". The term "communality" is understood to mean the automatic correlation that is reproduced for each and every characteristic. It is a measure of the degree to which the deviation of a characteristic can be explained by the factor system found.

Factor analysis methods construct the individual factors one after another in such a way that these factors achieve the best possible reproduction of the existing correlation matrix. Based on this assumption, the first factor will thus have the greatest influence in the entire system.

The coordinate system that is found can be modified by rotating the individual axes without changing the connections between the individual features. Figure 13 is an example of such a rotation for a two-dimensional coordinate system. The connections between characteristics M1 ... M6 cannot be clearly seen with respect to the original system (F1, F2). In the rotated coordinate system (F1', F2'), however, it is obvious that characteristics M1, M4 and M6 are determined substantially by the first factor F1' and characteristics M2 and M5 are determined by the second factor F2'. The charges of the characteristics are very small with respect to the other axis. Only characteristic M3 has large charges with respect to both factors. Hence, the factors can

be interpreted on the basis of the characteristics:  $F1'$  is explained by characteristics  $M4$  and  $M6$ , and  $F2'$  is explained by characteristics  $M2$  and  $M5$ .



**Figure 13. Rotation of the coordinate system**

Factor analysis thus makes it possible to:

- define a number of linearly independent factors which represent the common causes of the origin of the characteristics,
- determine the influence each parameter has on each factor,
- ascertain the extent to which the deviation of one parameter can be explained by the others (the "communalities" are a measure of this),
- determine the ranking of the characteristics with respect to a selected target parameter by a special rotation of the factor charges.

When this method is used to evaluate accident data, the problem of the missing values must be given special consideration. This is a problem that occurs frequently (because forms are incompletely filled out; because the starting material makes interpretation impossible, such as an interpretation of the driving speed prior to the collision). This problem can be resolved by not using the correlation matrix itself as the input matrix for the analytical method, but rather by using the matrix of the correlation coefficients that have been calculated for each pair of characteristics. This special point must be taken into account when interpreting the results.

Statistical analysis has been applied to a random sampling of  $n=3000$  accidents. Of these samples, 1,500 cases were selected on the basis of the front-to-rear type collision. The connections between the described accident characteristics were then investigated using the factor analysis procedure. Table 1 shows the rotated factor charges that are discussed below. It is clear that the use of extracted factors 1 to 4 makes fundamental connections between the characteristics obvious. It is of course also possible to expand this procedure to include other factors as well. This, however, in no way improves the validity in this particular case, since the sum of the inherent values of the correlation matrix reproduced on the basis of the factor solution found is greater or equal to the sum of the inherent values of the correlation matrix that is based on the system of characteristics (the condition that will abort the procedure). This means that the factor solutions that have been found can be used to explain at least 95 % of the total variance of the present system of characteristics.

As described above, the factor charges depicted in Table 3 are correlations between the characteristic and the factor, i.e. the factor is determined by the intensity (amount) of the correlation coefficient due to the characteristic (e.g. factor 1 correlates to 0.93 of the total extent of damage 01).

The characteristics, on the other hand, are determined on the basis of their correlations with the factors.

In the present case, factor 1 can be regarded as the factor for the accident sequence (the high correlation with the total extent of damage to both vehicles). Factor 2 represents the vehicle size of the driver causing the accident (output and mass) and factor 3 indicates the vehicle size of the person involved in the accident. Finally, the severity of the injuries and the age of the driver causing the accident predominate in factor 4.

The sex of both drivers, the original registration of the vehicle involved in the accident as well as the age and extent of injury to both drivers could not be explained on the basis of the factor system; the communalities for these characteristics are smaller than the maximum random value of the correlation coefficient which amounts to approx. 0.05 in 1,500 cases (with an error probability of 0.05). This means that the variations of these characteristics cannot be attributed to the other characteristics. They are either independent input parameters for this total system, or they are influenced by other characteristics not yet contained in the system. If the accidents can be described more extensively by supplying additional accident characteristics (in particular those describing the circumstances and sequence of events leading up to the accident), then one can rightly expect to uncover new findings in accident research by using the factor analysis method.

**Comparison with the United States** - The General Estimates Systems (GES) database contains a representative random sampling of the traffic accidents that have occurred in the United States of America. For the year 1994, there are 13,702 rear-end accidents in all locations contained in the random sampling totaling 55,759 accidents. The random sampling also includes rear-end accidents caused by or involving trucks. Compared with the results for Germany, the following similarities and differences were found with regard to rear-end accidents:

### Similarities

- a dominance of male drivers responsible with a high number of young and elderly drivers
- rear-end accidents usually occur on dry pavement (> 70%)
- rear-end accidents frequently occur at good visibility (no rain, fog) – approx. 75%
- drivers responsible frequently drive old vehicles (> 5 years)
- inattentiveness is virtually the sole reason for rear-end accidents
- low collision speeds, 63 % of all U.S. cases occur at less than 32 km/h (= 20 mph)

### Differences

- higher proportion of rear-end accidents at junctions and crossings in the U.S. (USA 44 %, Germany 27 % (mean value for country roads and the autobahn))
- more rear-end accidents in daylight in U.S. (USA 79%, Germany 55%)
- based on their share of traffic, luxury vehicles cause fewer rear-end accidents in U.S.; the opposite trend has been found for Germany
- the speed limits are lower in the U.S.: 50 % of all rear-ending vehicles occur while the vehicle is travelling slower than 32 km/h (=20 mph) and 78 % slower than 56 km/h (=35 mph)
- there is a greater number of rear-end accidents involving stationary vehicles in U.S. (86 % in the U.S., about 50 % in Germany)
- there is a greater number of rear-end accidents at junctions with traffic signals in U.S. (26 % USA, 14 % Germany)

### Additional findings for the U.S.

- in 72 % of all rear-end accidents, the driver responsible for the accident does not react to prevent the accident; in 11 % of all cases, he attempts to brake
- 90 % of all drivers causing accidents do not suffer injuries
- the influence of alcohol was cited in 3 % of all rear-end accidents

- the airbag activated in 1.4 % of all cases

**Table 3:**  
**Factors for the analysis of rear-end- accidents**

Characteristic	Factor 1 material damage	Rg Nr	Factor 2 guilty party (gp)	RgNr	Factor 3 Non guilty party (ngp)	RgN	Factor 4 accident severity	Rg Nr	commu- nalities
Total gp	0,93358	1	-0,18573	5	-0,10308	9	-0,06782	9	0,94991
Total ngp	0,80672	2	-0,19764	4	-0,22532	3	0,01076	13	0,72096
MAIS guilty driver	0,42002	3	0,0999	6	-0,09863	10	0,32505	1	0,27971
Output vehicle 1	-0,12242	6	-0,71879	1	0,13895	5	0,13	6	0,57293
Mass vehicle 1	-0,10722	7	-0,68235	2	0,19279	4	0,17961	4	0,54573
1 <sup>st</sup> Reg.1	-0,10202	8	-0,27499	3	0,10583	8	0,23722	3	0,15045
Output vehicle 2	0,08716	9	0,07107	8	0,63131	1	0,06496	10	0,42214
Mass vehicle 2	0,16691	4	6,98E-03	12	0,59017	2	-0,02734	11	0,37202
Age driver 1	-0,15343	5	0,01163	11	0,07663	12	0,30168	2	0,12546
MAIS driver 2	0,06347	10	0,01499	10	-0,07617	13	0,1434	5	0,03134
Age driver 2	4,76E-03	12	-0,07148	7	0,13354	6	0,06811	8	0,02788
1 <sup>st</sup> Reg. vehic- le 2	0,01156	11	0,02862	9	0,11802	7	0,01842	12	0,01522
Gender driver 1	1,16E-03	14	2,05E-03	13	-0,0777	11	-4,71E-03	14	6,06E-03
Gender driver 2	-1,50E-03	13	-1,47E-03	14	0,03758	14	0,08747	7	0,01016
Residuals:									
mean value:	5,44E-04		3,57E-04		1,98E-04		1,70E-04		
Minimum:	2,08E-04		3,69E-04		6,99E-04		1,19E-06		
Maximum:	0,54712		0,33685		0,08561		0,06419		

The differences shown above can be explained by, among other things, the difference in traffic conditions and the difference in driving behavior in both countries. The above-mentioned differences should also be taken into consideration when using the accident data.

#### **ACCIDENT AVOIDANCE AND SAFETY BENEFITS**

The safety benefits that can be achieved by putting the AAC system on the market can only be estimated, since there are no past figures available on the number of cars equipped, no past information on the system

properties of the standard product nor any practical experience, among other things.

Assuming that

- it is not possible to detect stationary objects
- that speeds exceed 40 km/h
- that all cars (100 %) are equipped with an AAC system
- that the system functions properly

first generation ACC systems would influence the outcome of approximately 40 % of all car to car rear-end accidents on country roads and 60 % on the autobahn.

Even if the focal point of rear end crashes with personal injuries is characterized by a crash into a stopping car or a car with a speed lower than 40 kph, the number of crashes which might be influenced by AAC is considerable:

autobahn	<ul style="list-style-type: none"><li>- approx. 7,000 rear-end accidents involving personal injury and about 12,000 persons involved in accidents (= approx. 27 % of all autobahn accidents involving personal injury)</li><li>- approx. 2,000 rear-end accidents involving severe material damage (= approx. 12 % of all autobahn accidents in this category)</li><li>- approx. 20,000 rear-end accidents involving minor material damage (= approx. 12 % of all autobahn accidents in this category)</li><li>- reduction in accident costs by approx. 440 million Deutschmarks</li></ul>
country road	<ul style="list-style-type: none"><li>- approx. 7,100 rear-end accidents involving personal injury and 11,000 persons involved in accidents (= approx. 6 % of all accidents involving</li></ul>

personal injury on country roads)

- approx. 1,100 rear-end accidents involving severe material damage (= approx. 3 % of all accidents in this category on country roads)
- approx. 11,000 rear-end accidents involving minor material damage (= approx. 3 % of all autobahn accidents in this category)
- reduction in accident costs by approx. 350 million Deutschmarks

The cost volume was estimated using recognized cost records (Deffke et al, 1995). Zierden (1997) cites a value of 36,000 Deutschmarks as an orientation value for the average amount of damage in rear-end accidents involving personal injury. This value contains an amount of 17,000 Deutschmarks for material damage and 19,000 Deutschmarks for personal injury and has been calculated from rear-end accidents in all road classes. The comparatively low average is explained by the low subsequent damage in the case of rear-end accidents.

In view of the fact that in the foreseeable future only a small number of vehicles will be equipped with the ACC system (only newly registered cars) and bearing in mind that there is only a limited possibility of avoiding rear-end collisions, it can justifiably be said that the practical impact of first generation of ACC systems will be lower by a factor of 10. This would then mean that the first generation ACC system will influence the outcome of less than 2 % of all autobahn accidents and less than 0.3 % of all accidents occurring on country roads.

These percentages are very low, although the safety benefits to persons involved in accidents and potential material damage must not be overlooked. If 10 % of all cars were equipped and the above-mentioned assumptions are applicable, then the safety benefits (per year) would still amount to about 2,300

persons involved in accidents and approximately 80 million Deutschmarks.

## SYSTEM REQUIREMENTS AND OUT-LOOK

Traffic safety can be improved by developing new technologies. As becomes clear using the ACC system as an example, such systems must be highly efficient to make their influence felt in traffic accidents. In the case of the ACC system, it appears imperative to make detection of stationary and slowly traveling vehicles possible, to enhance the efficiency of the system and to extend its field of application to country roads and streets within city limits.

Since drivers cause rear-end accidents as a rule out of inattentiveness and since the regulatory process is subject to comparatively simple marginal conditions, the development of the ACC system is basically promising for situations involving rear-end accidents. More details about the speeds in rear-end accidents and the follow-up costs of the accidents are necessary in order to be able to more exactly differentiate costs and benefits.

## ACKNOWLEDGEMENTS

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# ANALYSIS OF DRIVER-VEHICLE-INTERACTIONS IN AN EVASIVE MANOEUVRE - RESULTS OF „MOOSE TEST“ STUDIES

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## ABSTRACT

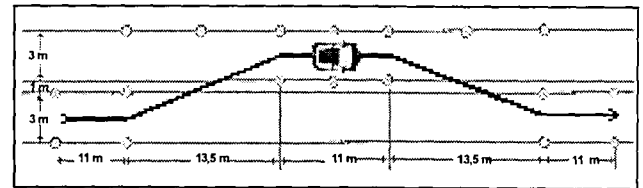
In 1997 a so-called „moose test“, an evasive manoeuvre without braking at a speed between 60 and 65 km/h, led to improvements in the Mercedes A-class after two vehicles rolled over in this manoeuvre. The new A-class was presented to the press in January '98: more than 450 journalists from all over Europe tested the improved vehicle during a vehicle dynamics workshop at the Goodyear Proving Ground in Mireval/France. Five vehicles were equipped with data acquisition units providing data on the driver's input at steering wheel (angle and velocity) and foot pedals as well as on vehicle reactions (speed, lateral acceleration, yaw rate) and the interference of the Electronic Stability Programme (ESP). More than 2.000 tests conducted by over 400 journalists and experts were analysed in detail and compared to 131 moose tests performed by normal drivers. In addition, 30 normal drivers drove more than 15.000 km in real road traffic. The evaluation produces characteristic values of driver performance in extreme evasive manoeuvres on a test track compared with normal driving. The influences of individual driving style on test performance are analysed.

## INTRODUCTION

The enhancement of Active Safety requires detailed data on driver-vehicle-interactions in critical driving situations. Based on the concept of "Real Life Safety", Daimler-Benz conducts test series with experts and with normal drivers at the Daimler-Benz driving simulator and in real world. Besides studies on driver behaviour, which form the basis for the development of assistance systems, standard manoeuvres are applied to verify the active safety of Mercedes vehicles at the highest level possible (e.g. ISO lane change).

The so-called "moose-test", which was not known in Germany before 1997, is supposed to test vehicle reactions in an emergency steering manoeuvre at (constant) speeds above 60 km/h (Figure 1). In order to assess the value of this manoeuvre as a test procedure for vehicle

stability, the questions of test objectivity, reliability and validity have to be answered.



**Figure 1. "Moose-Test".**

In order to generate a sound basis for the evaluation of driver behaviour in this specific evasive manoeuvre, different driver groups are included: experts, motor journalists and normal drivers. Field tests with normal drivers serve to provide measures of steering behaviour in real road traffic (Table. 1). Results are also utilised for the evaluation of the "moose-test".

**Table 1.**  
**Data Base: Number, Conditions and Subjects of Tests**

CONDITIONS	DRIVERS		
	Experts	Journalists	Normal Drivers
<b>Proving Ground ("Moose-tests")</b>	<i>Goodyear (France)</i> 12 drivers, 100 tests	<i>Goodyear (France)</i> 399 drivers, 1.957 tests	<i>Mercedes (Germany)</i> 30 drivers, 131 tests
<b>Real Road Traffic</b>			<i>Field Tests (Germany)</i> 30 drivers, 15.583 km



## "MOOSE-TESTS"

### Procedure

During the workshop journalists were given the opportunity to test the new A-class in 5 different manoeuvres. One of them was the "moose-test", where 5 vehicles were equipped with data acquisition devices to record measures of driver behaviour and dynamic vehicle reactions (Table 2). Two of these vehicles were loaded with additional weight (3\*68 kg) on the back seats. It was noted for each test whether pylons were knocked over.

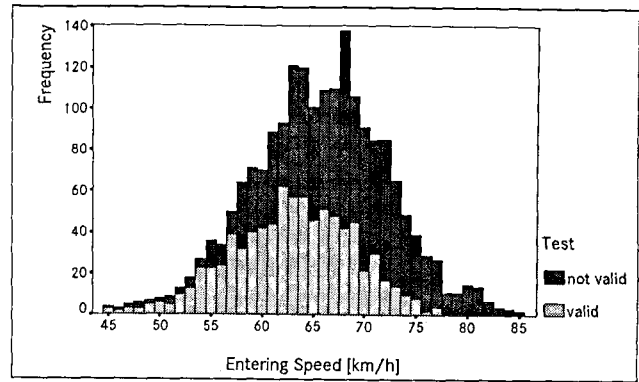
**Table 2.**  
**Data Obtained to Quantify Driver-Vehicle Interactions During the "moose-test"**

Category	Measures
Driver Behaviour	vehicle speed
	steering wheel angle
	steering wheel velocity
	brake actuation
Dynamic Vehicle Reactions	lateral acceleration
	yaw velocity
	ESP-lamp
Test Performance	passed vs. not passed

Journalists were given information about the manoeuvre several times in advance, especially about the recommended speed for their first "moose-test" (50-70 km/h) and about the fact that braking within the manoeuvre is not allowed. They were free to choose a vehicle without acquisition devices if they did not want to be measured. Journalists who took one of the measuring vehicles were given feedback on their performance at the end of the workshop. Most of the participants drove at least 4 times. Usually vehicles were occupied by 2 journalists.

### Entering Speed

Entering speed varied from 40 up to 85 km/h (mean 68 km/h), for valid tests up to 82 km/h (mean 62 km/h, Figure 2). Each journalist performed several tests, mean individual maximum entering speed for a valid test is 65 km/h. Speed decreased in the course of most tests (mode: - 7 km/h).

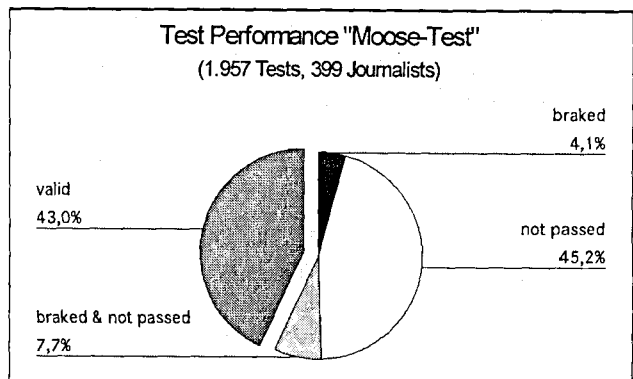


**Figure 2. Frequency Distribution of Entering Speed for Valid and for Invalid "Moose-Tests" (399 Journalists, 1.957 Tests).**

### Test Performance

Tests were rated as valid if the driver did not brake or knock over pylons. In 11,8% of all tests, the brake pedal was actuated - 14% of 399 journalists did brake during their first test (Figure 3). Most of them were not aware of this fact when asked afterwards. This indicates that braking is included in many persons' subconscious reaction programme in a critical driving situation.

In 53% of all 1.957 tests, pylons were knocked over. This finding may be attributed to the difficulty of the manoeuvre as well as to the specific motivation of some journalists to test the behaviour of the A-class at the driving limits regardless of manoeuvre requirements. 43% of all tests are rated as valid and form the basis for further evaluation.



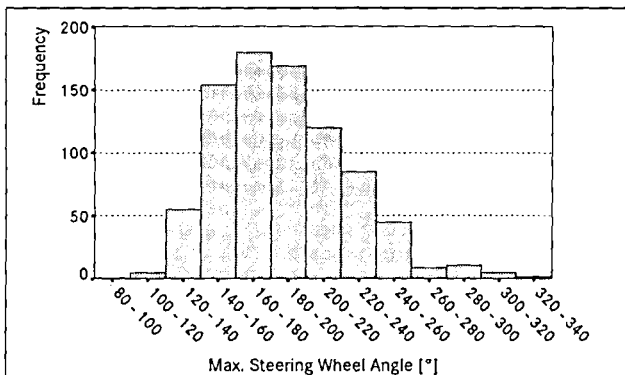
**Figure 3. Test Performance of 399 Journalists in 1.957 "Moose-Tests".**

## Adaptation Effects

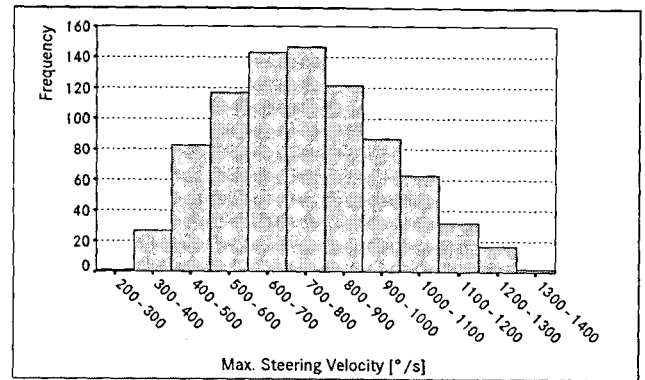
Changes in the individual behaviour in the course of several tests were expected due to increasing adaptation to vehicle and manoeuvre. Yet test performance does not increase, instead the percentage of valid tests decreases over 5 or more runs from less than 50% down to around 20%. This can be explained by a significant increase in speed. For valid tests, the mean increase in entering speed is 10%.

## Steering Behaviour

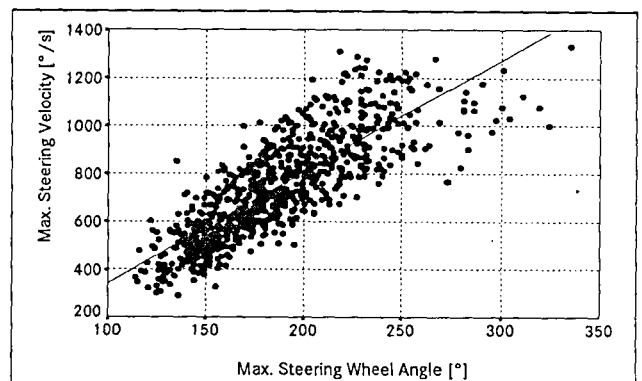
Interindividual variations in steering behaviour are considerably high: maximum steering wheel angles vary between  $98^\circ$  and  $335^\circ$  in valid tests (mean  $187^\circ$ , Figure 4). Maximum steering velocity ranges between 292 and  $1.335^\circ/\text{s}$  (mean  $746^\circ/\text{s}$ , Figure 5). In 77% of all valid tests the maximum occurs when steering into the 3<sup>rd</sup> lane, in 22% the maximum occurs when stabilising in the 2<sup>nd</sup> lane. Values for maximum steering wheel and maximum steering velocity are correlated ( $r^2=0,67$ ), Figure 6. Maximum values of yaw velocity range between 21 and  $55^\circ/\text{s}$  (mean  $37^\circ/\text{s}$ , Figure 7), of lateral acceleration between  $4,2$  and  $12,1 \text{ m/s}^2$  (Figure 8).



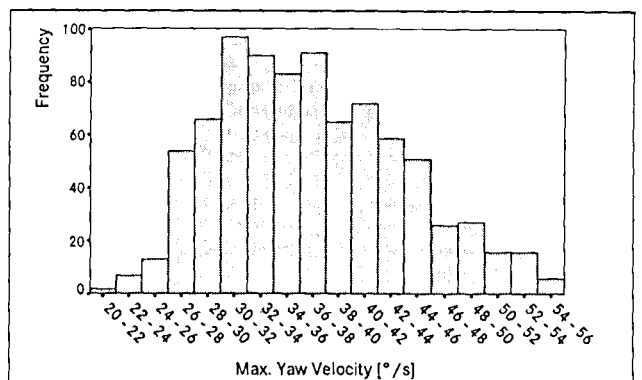
**Figure 4.** Frequency Distribution of Maximum Steering Wheel Angle (841 Valid "Moose-Tests" by 399 Journalists).



**Figure 5.** Frequency Distribution of Maximum Steering Velocity (841 Valid "Moose-Tests" by 399 Journalists).



**Figure 6.** Maximum Steering Velocity as a Function of Maximum Steering Wheel Angle (841 valid "Moose-Tests" without ESP-Interference, Linear Regression:  $r^2 = 0,67$ ).



**Figure 7.** Frequency Distribution of Maximum Yaw Velocity (841 Valid "Moose-Tests" by 399 Journalists).

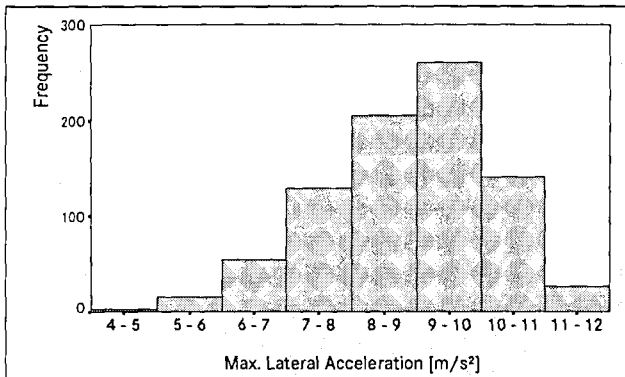


Figure 8. Frequency Distribution of Maximum Lateral Acceleration (841 Valid "Moose-Tests" by 399 Journalists).

### ESP-Interference

26% of all valid tests were conducted without ESP-interference at entering speeds of up to 74 km/h (mean 58 km/h, Figure 9)). Especially steering wheel velocity is significantly lower for tests without ESP-interference (mean: 523 °/s vs. 824 °/s for tests with ESP-support).

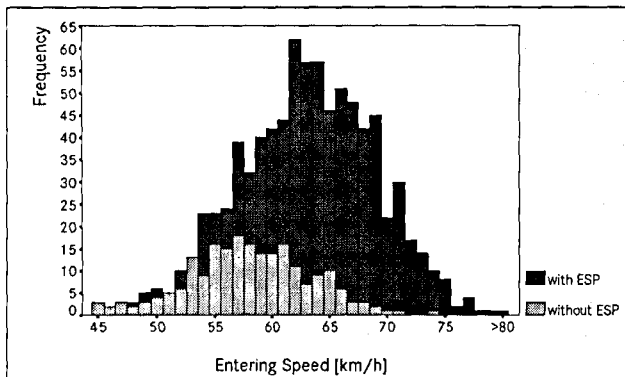


Figure 9. Frequency Distribution of Entering Speed for "Moose-Tests" with and without ESP-Interference (841 Valid Tests by 399 Journalists).

### Loading and Road Surface

The percentage of valid tests was lower on wet road surface (205 tests) than on dry road surface (38 vs. 44%). While entering speeds did not differ significantly, values for lateral acceleration and yaw velocity were significantly lower (Table 3).

Table 3.

Significant Differences in Valid "Moose-Tests" on Dry (n=764) and Wet (n=77) (Differences: dry = 100%)

Measure		Surface		$\Delta$
		dry	wet	
ESP-Interference	[%]	75	69	- 8,0 %
Lateral Acceleration	[m/s <sup>2</sup> ]	8.9	8.5	- 4,5%
Max. Steering Velocity (Steering into 2 <sup>nd</sup> lane)	[°/s]	148	121	- 18,2%
Max. Yaw Velocity				
Steering into 2 <sup>nd</sup> lane	[°/s]	29	26	- 10,3%
Stabilising in 2 <sup>nd</sup> lane	[°/s]	34	32	- 5,9%

Test in vehicles with maximum total mass do not differ in terms of test performance and steering behaviour. Entering speeds and lateral acceleration are slightly lower, yaw velocity is higher (Table 4). More tests were supported by ESP in vehicles with maximum total mass.

Table 4.

Significant Differences in Valid "Moose-Tests" in vehicles without additional loading (n=472) and in vehicles with maximum total mass (n=369) (Differences: without additional loading = 100%)

Measure		Mass		$\Delta$
		< max	max	
ESP-Interference	[%]	69	81	+ 17,4%
Entering speed	[km/h]	64	61	- 4,7%
max. lat. acceleration	[m/s <sup>2</sup> ]	9,0	8,7	- 3,3%
max. yaw velocity				
steering into 2 <sup>nd</sup> lane	[°/s]	27	29	+ 7,4%
steering into 3 <sup>rd</sup> lane	[°/s]	33	36	+ 9,1%
stabilising in 3 <sup>rd</sup> lane	[°/s]	32	36	+ 12,5%

### Experts vs. Journalists

Compared to journalists, experts for vehicle dynamics from Mercedes-Benz perform „moose-tests“ at significantly higher speeds with lower values for steering wheel angle and steering velocity (see example in Figures 10-11).

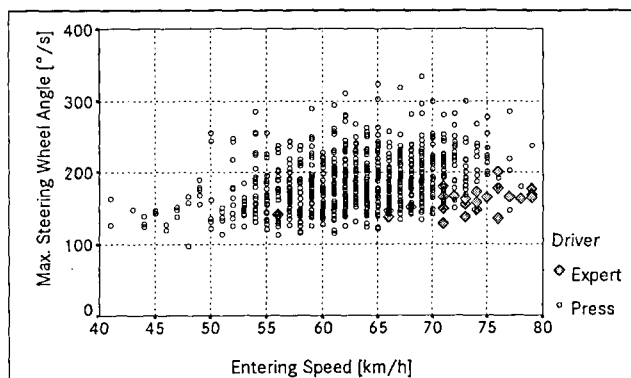


Figure 10. Maximum Steering Wheel Angle as a Function of Entering Speed in valid tests (Journalists vs. Expert Driver).

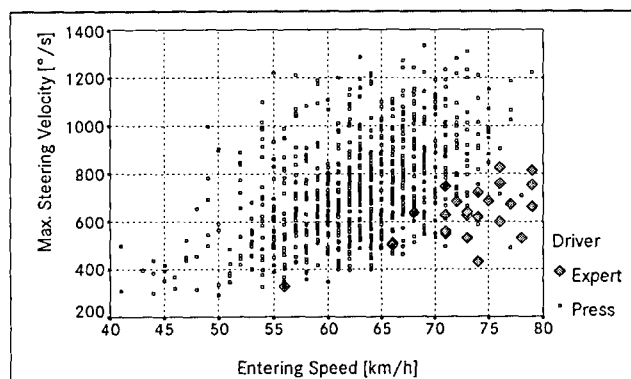


Figure 11. Maximum Steering Velocity as a Function of Entering Speed in valid tests (Journalists vs. Expert Driver).

### Normal Drivers

30 normal drivers performed the „moose-test“ at the Mercedes test track in Stuttgart with one of the test vehicles (without additional loading, dry road surface). 77 out of the 131 tests were valid (59%; journalists: 43%), 40 out of which without ESP-support (52% vs. 26%). In 11,5 % of all tests the brake pedal was actuated (vs. 14,5%). Values for entering speed and steering velocity were significantly lower than those of the journalists. The relation between maximum steering wheel angle and steering velocity is equal for normal drivers and journalists (Figures 12 and 6).

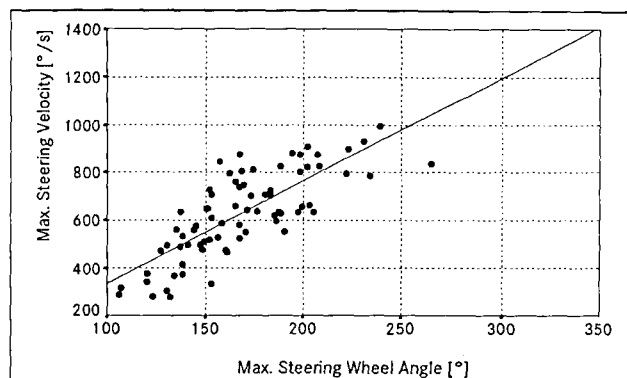


Figure 12. Maximum Steering Velocity as a Function of Maximum Steering Wheel Angle (77 Valid „Moose-Tests“ by 30 Normal Drivers, Linear Regression:  $r^2 = 0,61$ ).

## FIELD TESTS

### Procedure

30 subjects took part in field experiments (Table 5). They were given one of the test vehicles for one or two days with the instruction to drive approx. 500 km, mainly on state and country roads. As the A-class is a very new product, none of the subjects was familiar with the test vehicle before.

Data on driver behaviour and vehicle reactions was stored at a frequency of 50 Hz. Subjects were interviewed after the test and provided additional information on driving conditions. A total distance of over 15.000 km was recorded. 17 tests were conducted under wet road conditions.

Table 5.  
Field Tests with 30 subjects (14 female, 16 male):  
Sample Description (Minimum, Mean  $\pm$  Standard  
Deviation, Maximum)

Measure		min	$\bar{x} \pm sd$	max
Age	[a]	19	$34 \pm 10$	56
Driving Experience	[1000 km/a]	20	$376 \pm 320$	1.500
Distance	[km/subject]	109	$519 \pm 181$	938
Max. Speed	[km/h]	107	$160 \pm 22$	199
Passengers		0	$1,4 \pm 1,0$	4

## Driver Behaviour

As expected (Bielaczek et al., 1996), measures of steering behaviour are closely related to speed: maximum values of steering wheel angle and steering velocity decrease over speed (Figures 13-14) like yaw velocity and lateral acceleration (Figures 15-16). Variations within the speed categories are assumed to be caused by differences in driving style, traffic and route characteristics (Breuer et al., 1996) which will be the matter of future analyses.

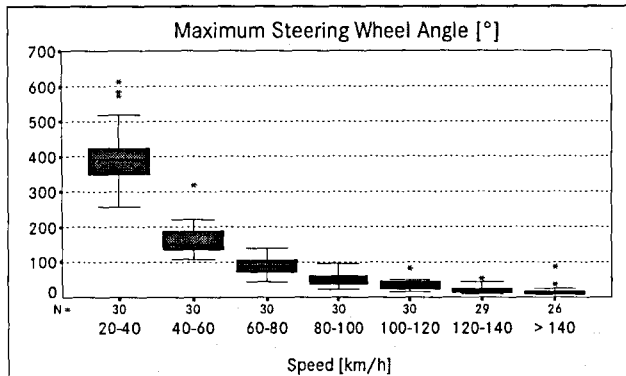


Figure 13. Boxplot of Maximum Steering Wheel Angle as a Function of Speed (30 Field Tests with Normal Drivers).

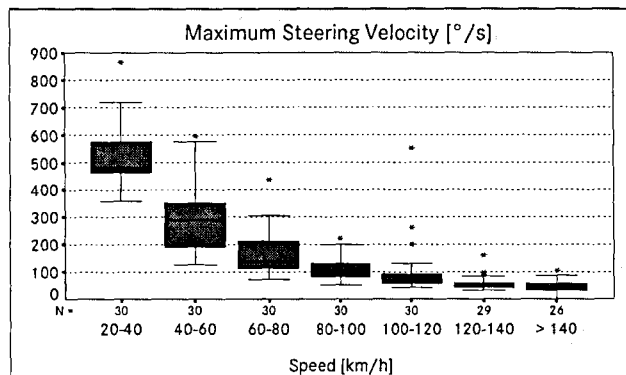


Figure 14. Boxplot of Maximum Steering Velocity as a Function of Speed (30 Field Tests with Normal Drivers).

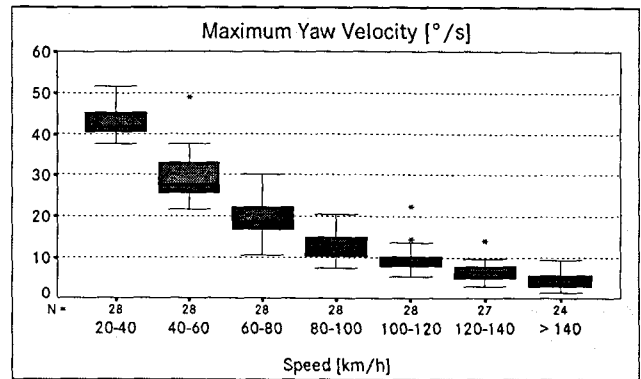


Figure 15. Boxplot of Maximum Yaw Velocity as a Function of Speed (30 Field Tests with Normal Drivers).

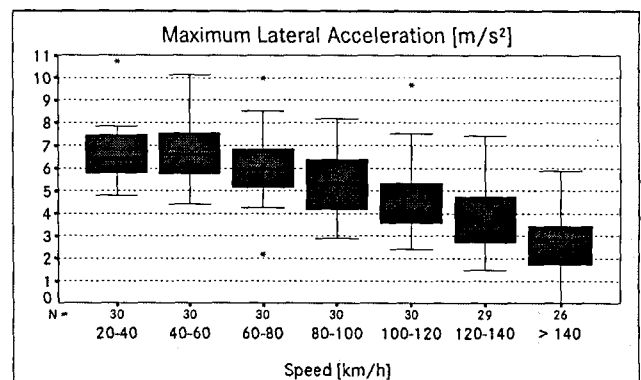
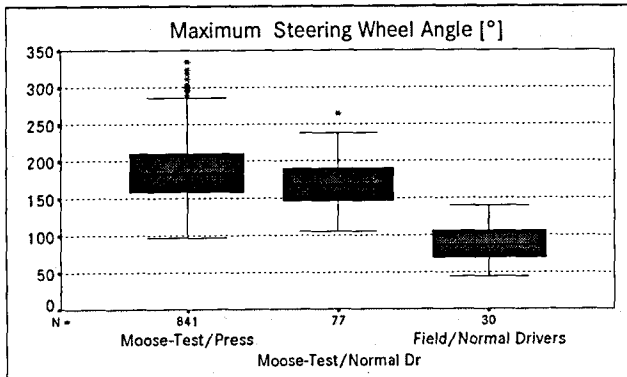


Figure 16. Boxplot of Maximum Lateral Acceleration as a Function of Speed (30 Field Tests with Normal Drivers).

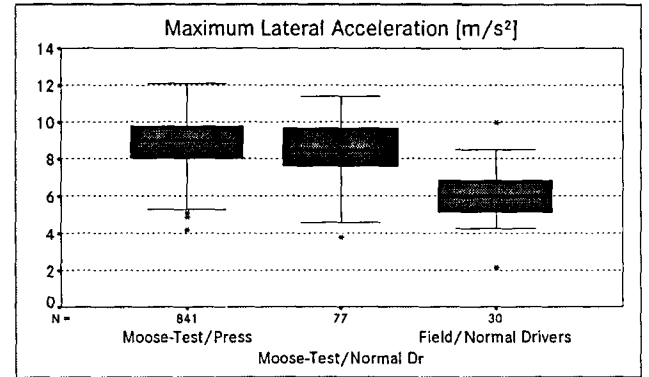
## DISCUSSION

Objective data prove that the new A-class passes the "moose-test" even at high speed. Depending on steering behaviour, the test can be passed at speeds up to 74 km/h without interference of ESP.

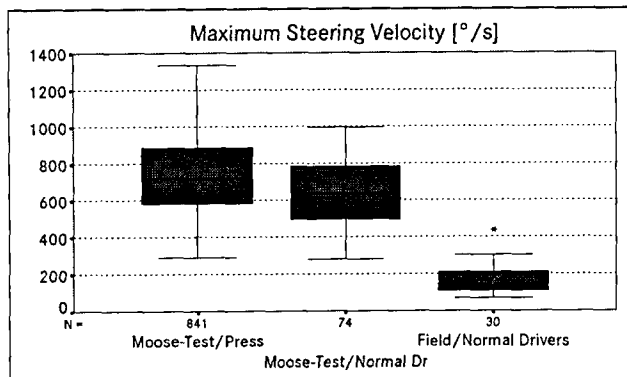
Steering reactions in this manoeuvre are extreme compared to real road traffic: steering wheel angles between 98 and 335° (mean 187°), steering velocity between 292 and 1.335°/s (mean 746°/s) and yaw velocity between 21 and 55°/s (mean 37°/s). As can be seen in Figures 17-20, the values obtained in "moose-tests" are far from those obtained in real road traffic at comparable speeds between 60 and 80 km/h.



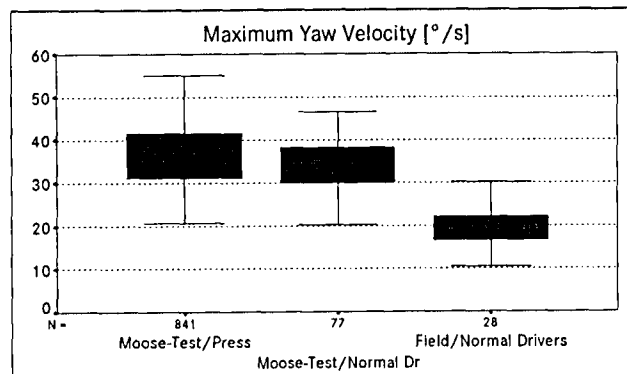
**Figure 17. Boxplot of Maximum Steering Wheel Angle for 399 Journalists and 30 Normal Drivers in Valid „Moose-Tests“ and for 30 Normal Drivers in Real Road Traffic at a Driving Speed Between 60 - 80 km/h.**



**Figure 20: Boxplot of Maximum Lateral Acceleration for 399 Journalists and 30 Normal Drivers in Valid „Moose-Tests“ and for 30 Normal Drivers in Real Road Traffic at a Driving Speed Between 60 - 80 km/h.**



**Figure 18. Boxplot of Maximum Steering Velocity for 399 Journalists and 30 Normal Drivers in Valid „Moose-Tests“ and for 30 Normal Drivers in Real Road Traffic at a Driving Speed Between 60 - 80 km/h.**



**Figure 19. Boxplot of Maximum Yaw Velocity for 399 Journalists and 30 Normal Drivers in Valid „Moose-Tests“ and for 30 Normal Drivers in Real Road Traffic at a Driving Speed Between 60 - 80 km/h.**

Performance in the "moose-test" with a given vehicle is mainly determined by the individual steering behaviour which is dependent on the driver's capabilities and motivation. Significant differences between groups of drivers (motor journalists, expert drivers, normal drivers), high variations within the groups and considerable intraindividual variations lead to the conclusion that this manoeuvre cannot be classified as an objective and reliable test for the active safety of a car.

The "moose-test" is supposed to test the vehicle reactions in an evasive manoeuvre caused by an obstacle which suddenly appears in front / at the right hand side of the vehicle. In earlier research work at Daimler-Benz concerning driver behaviour in critical situations (driving simulator and real vehicles, different kinds of obstacles, different speeds from 60 -120 km/h), braking or braking combined with steering were found as the most frequent reaction. Drivers who tried to cope by steering produced lower values for steering wheel angles and steering velocities than those found in the "moose-test" (see e.g. Zomotor, 1991). So it can be said that the test procedure requires a driving behaviour which does not seem to be typical for all drivers in critical situations.

Within the concept of Real Life Safety, further work at Daimler-Benz will concentrate on the detailed analysis of real driver behaviour in critical situations in order to derive realistic, objective and efficient test procedures and design criteria for enhanced Active Safety.

## REFERENCES

Bielaczek, C.; Barz, M.; Breuer, B.; Breuer, J.; Rohmert, W.: Development of Warning Strategies and Driver-Vehicle Interfaces. Fifteenth International Technical Conference on the Enhanced Safety of Vehicles (ESV) Melbourne, Australia, May 13-17, 1996 Washington, D.C. (USA): Department of Transportation 1996

Breuer, J.; Rohmert, W., Breuer, B.; Bielaczek, C.: Human Determinants of Active Safety: Results of Interdisciplinary Driver Behaviour Experiments. Fifteenth International Technical Conference on the Enhanced Safety of Vehicles (ESV) Melbourne, Australia, May 13-17, 1996. Washington, D.C. (USA): Department of Transportation 1996

Zomotor, A.: Fahrwerktechnik: Fahrverhalten. Würzburg: Vogel 1991

## ACKNOWLEDGEMENT

*This paper is dedicated in deep gratefulness to my father, Professor Dr. Bert J. Breuer, who strongly promoted and successfully encouraged both research work and research workers in the fields of man-machine-interactions in road traffic safety.*

## ABS PERFORMANCE ON GRAVEL ROADS

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**Steven Ribarits**

University of British Columbia

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Transport Canada

**Barry Chafe**

Royal Canadian Mounted Police

Canada

Paper Number 98-S2-W-36

### ABSTRACT

Anti-lock brake systems (ABS) have become common on most passenger cars and light trucks in North America yet ABS braking performance can vary widely between vehicle makes and on different road surfaces.

The present ABS designs restrict wheel lockup which may be inefficient for gravel and snow covered roads where locked wheels can produce much higher deceleration rates. Based on the growing number of public complaints of poor braking on gravel roads, tests were conducted to determine the performance variation between vehicles with different ABS controllers and between the same vehicle with and without its ABS activated. Significant deceleration differences were noted.

### INTRODUCTION

The approximate equal kilometers of paved to unpaved roads in the western USA and Canada suggests that ABS design must include road surface type detection and 'best method' braking algorithms for different surfaces.

This paper presents test data on six ABS equipped vehicles and one non ABS equipped vehicle while braking on gravel roads with the ABS activated and deactivated. ABS tests were also run on dry pavement for each vehicle to establish a base line deceleration value.

### TEST CONDITIONS AND PROCEDURES

#### Test Road Surfaces

A well traveled, bituminous asphalt surfaced road was chosen for the base line brake tests. The road had a -1.5% to -1.8% grade in the test direction and was in good repair. An adjacent, recently graded, loose gravel road was chosen for the comparison brake tests. It also had a grade of -1.5% to -1.8% in the test direction. Samples were taken of the gravel surface for sieve analysis. The analysis was conducted by the Geotechnical and Materials Branch of the BC Ministry of Transportation and Highways according to ASTM C136, C117. The grain size distribution chart is shown in Appendix A. The weather was dry, calm, 15° C with partial cloud cover.

### Test Vehicles

The seven vehicles tested were:

- 1993 GMC Suburban 4x2, automatic, RWD
- 1995 GMC Suburban 4x4, automatic, tested in 2WD
- 1994 GMC Yukon 4x4, automatic, tested in 2WD
- 1994 Ford F150 XL 4x4, standard, tested in 2WD
- 1993 Ford Explorer 4x4, automatic, tested in 2WD
- 1996 Chevrolet Cavalier, automatic, FWD
- 1991 Ford Crown Victoria (not ABS equipped), automatic, RWD

All vehicles were inspected before testing and were in good mechanical repair. Further vehicle and tire information is contained in Appendix B, Tables 1 and 2.

### Instrumentation

**G-Analyst** - This commercially available tri-axial accelerometer was used in each vehicle to record deceleration values. The data was captured at a sample rate of 10 Hz and then downloaded to a computer for graphing. The resolution, measured in units of gravity (g), is  $\pm 0.01$  g. The accelerometer was placed at floor level close to the vehicle's centre of gravity and pitch and roll settings were set to zero g/g to obtain unaltered values.

**Vericom VC2000PC** - This is also a commercially available accelerometer which measures in one plane, samples at 100 Hz and has a resolution is  $\pm 0.001$  g. It has a pre-set factory calibration for vehicle pitch. It was used in conjunction with the g-analyst to capture ABS modulations near 10 Hz which may not be captured by the G-analyst.

**Kustom Falcon Radar** - This hand held unit's calibration was checked before testing and was operated by trained police officers to determine the test vehicle speed at braking. The unit has a resolution of  $\pm 1$  km/h.

**Bumper Gun** - A brake light activated bumper gun was used to mark the point of first brake application. The distance from the shot mark to the stopped vehicle provided the total stopping distance.

### Test Procedures

Each test vehicle was inspected, documented and



weighed. The instrumentation was installed and calibrated as per the manufacturer's instructions. The Vericom was set to 'auto start' which begins recording once a 0.2 g threshold is exceeded.

Three test conditions of high effort brake application, in straight line braking from 50 km/h, were run for each vehicle: 1) on dry pavement; 2) on gravel with ABS activated and 3) on gravel with ABS deactivated. A minimum of three tests were run under each condition, more if there was a discrepancy greater than 10% between the measured values. A driver and observer of approximately equal weight were onboard for every test. G-analyst and Vericom data were down-loaded and radar speed and total stopping distance recorded. Several brake tests were run at higher speeds to observe vehicle rotation on the gravel surface.

## TEST RESULTS

### Bumper Gun

Appendix C, Table 3, contains the tabular results derived from the bumper gun measurements. Averages of the speed and stopping distance of at least three runs were taken for each test condition. Test runs at higher speeds to observe directional control were not included in the averages. The deceleration value,  $a$ , was calculated from equation (1.):

$$a = S^2 / (254 \times d) \quad (1.)$$

where:  $a$  is deceleration in g  
 $S$  is speed in km/h  
 $d$  is stopping distance in meters

The slope influence (-1.5% to -1.8%) was corrected to a level surface by adding 0.02 g to each test result.

A moderate to significant improvement in braking without ABS was observed. Percent differences between ABS on and off on the gravel surface ranged from 10% for the Ford F150 (rear wheel only ABS) to 38% for the Chevrolet Cavalier (all wheel ABS). The second largest difference (33%) was for the 1993 GMC Suburban.

In no test did the ABS provide equal or higher deceleration values. In no test was there appreciable vehicle rotation with the ABS deactivated, even at speeds up to 77 km/h.

### G-analyst and Vericom

Table 4 in Appendix C summarizes the averaged values from the G-analyst and Vericom accelerometers for each test surface condition. The first and last 0.5 second of each braking event were ignored in calculating the G-analyst average. This gives an average maximum deceleration by eliminating the initial ramp-up and final

ramp-down values. The G-analyst values were also corrected for road gradient. The Vericom's internal software provided an average deceleration for each test run. These were then averaged for each of the three test conditions.

Variation between the G-analyst and Vericom data sets is small, typically less than 5% for the gravel test values.

A percent difference in braking deceleration was also calculated for the gravel surface condition with the ABS on and off. As with the bumper gun results, decelerations improved in each case with the ABS deactivated.

Appendix D contains G-analyst plots of braking on the gravel surface with and without ABS for test vehicles 1 to 6. In each case, the plots clearly show a significant difference in braking between the ABS on and off. Test vehicle 4 shows the least difference possibly because only the rear wheels are ABS controlled. A higher speed of 66 km/h was also included to show that speed has little influence on the braking values. Test vehicle 7 was not included because it was not ABS equipped.

## CONCLUSIONS

Comparative brake testing of specific vehicles on a gravel surface shows significant performance differences with ABS on and off. Averaged G-analyst deceleration values with ABS deactivated range between 0.59 and 0.66 g while values with ABS activated range from 0.37 to 0.52 g. This translates into increased stopping distances for one test vehicle of up to 60%. The highest value with ABS activated, 0.52 g, was from test vehicle 4 which had rear wheel only ABS.

The ABS control logic of the test vehicles does not utilize the potential maximum deceleration rate which locked wheels may achieve on gravel. It should be noted that no appreciable vehicle rotation occurred with the ABS deactivated even at speeds up to 77 km/h.

Further refinement in ABS should consider a 'best method' braking approach which could include wheel lock up on some surfaces.

The measured performance of these vehicles is not necessarily indicative of ABS performance of other vehicle models under similar test conditions and caution should be used in extrapolating these results. Further testing is required to determine different vehicles' ABS performance characteristics.

## ACKNOWLEDGMENTS

The authors wish to thank the Sicamous Area Roads Maintenance Manager for assistance in road preparation and the Thomson-Okanagan Geotechnical and Materials Branch of BC Ministry of Transportation and Highways for gravel analysis.

## APPENDIX A

### SIEVE ANALYSIS OF THE GRAVEL TEST ROAD SURFACE

GEO TECHNICAL AND MATERIALS ENGINEERING  
MINISTRY OF TRANSPORTATION AND HIGHWAYS  
PROVINCE OF BRITISH COLUMBIA

SOILS AND AGGREGATE LABORATORY  
THOMPSON - OKANAGAN REGION

### SIEVE ANALYSIS SUMMARY REPORT - ASTM C136, C117

GRAN\_SVE.XLW

Rev. 6/18/94

Project: TAC STUDY  
Project No.: 241-05930-3000  
Material: Pit Run  
Sample Source: ROAD BASE  
Client: TRANSPORT CANADA

Sample No.: N/A Bag No.: PAIL  
TP / TH #: GRAB Depth: SURFACE  
Date Rec'd: OCT31/97 Date Tested: NOV3/97  
Tested By: H.L.  
Sampled By: M. Macnabb Lab. No.: 610-1

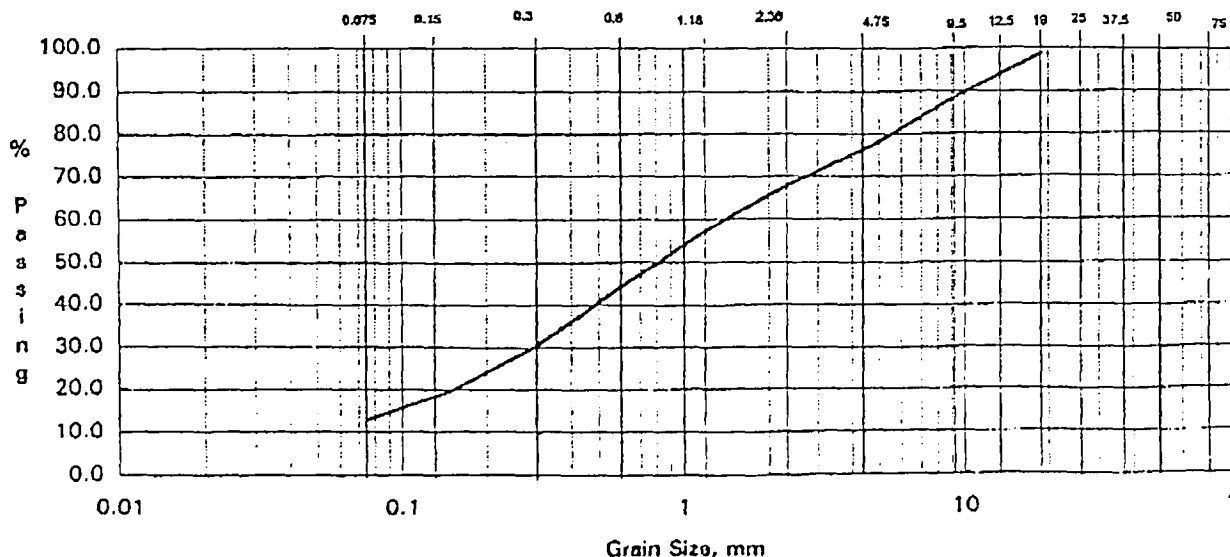
Sieve Fraction Size, mm	Cumulative % Passing	MOT Specifications
75		
50		
37.5		
25		
19	98.8	
16		
13.2		
12.5		
9.5	88.9	
6.3		
4.75	77.4	
2.36	68.1	
1.18	57.2	
0.6	44.2	
0.3	30.3	
0.15	19.7	
0.075	13.0	

Test Mass 8101.1 gm

Deg Fracture SE PI %  
% Gravel 22.6 Cc 1.3  
% Sand 64.5 Cu 29.8  
% Fines 13.0 USCS SM1

Comments:  
HARD & ANGULAR ROCK  
SILTY SAND WITH GRAVEL

Grain Size Distribution Chart



## APPENDIX B - TEST VEHICLE INFORMATION

Table 1.  
Vehicle Information

Test Vehicle	Year	Make / Model	ABS Make/ Model	milcage (km)	weight (kg)
1	1993	GMC Suburban	KH* EBC 4	118,834	2,850
2	1995	GMC Suburban	KH EBC 310	8,267	2,875
3	1994	GMC Yukon	KH EBC 4	83,692	2,675
4	1994	Ford F150 XL	RABS II	43,384	2,650
5	1993	Ford Explorer	Teves Mark IV	65,809	2,200
6	1996	Chevrolet Cavalier	Delco VI	17,332	1,600
7	1991	Ford Crown Victoria	N/A	138,956	2,150

\* Kelsey-Hayes Company

Table 2.  
Tire Information

Test Vehicle	Tire Make	Size	Depth (mm)	Pressure (kPa)
1	Michelin LTX	245/75R16	4	220
2	Firestone Steeltex A/T	245/75R16	12	220
3	Firestone Steeltex A/T	245/75R16	6	220
4	Goodyear Wrangler RT/S	265/75R15	7	220
5	Michelin LTX	235/75R15	8	220
6	BF Goodrich Touring T/A	195/65R15	7	220
7	Bridgestone WT11	225/70R15	4	220

## APPENDIX C - TEST RESULTS

Table 3.  
Bumper Gun Results

Test Vehicle	ABS	Surface Condition	Average Speed (km/h)	Average Stop Distance (m)	Raw Accel (g)	Slope Adjust Accel (g)	% Diff 1-(On/Off)
1	ON	Pavement	49.3	13.45	0.71	0.73	
	ON	Gravel	49.0	26.22	0.36	0.38	
	OFF	Gravel	50.7	18.32	0.55	0.57	33.3
2	ON	Pavement	48.8	15.80	0.59	0.61	
	ON	Gravel	49.0	21.90	0.43	0.45	
	OFF	Gravel	48.0	17.04	0.53	0.55	18.2
3	ON	Pavement	49.5	16.61	0.58	0.60	
	ON	Gravel	49.7	25.35	0.38	0.40	
	OFF	Gravel	49.7	18.78	0.52	0.54	25.9
4	ON	Pavement	49.7	13.76	0.71	0.73	
	ON	Gravel	49.7	19.28	0.50	0.52	
	OFF	Gravel	48.3	16.32	0.56	0.58	10.3
5	ON	Pavement	50.8	15.35	0.66	0.68	
	ON	Gravel	49.3	20.68	0.46	0.48	
	OFF	Gravel	47.0	15.28	0.56	0.58	17.2
6	ON	Pavement	53.0	12.72	0.87	0.89	
	ON	Gravel	50.3	25.02	0.40	0.42	
	OFF	Gravel	52.0	16.15	0.66	0.68	38.2
7	OFF	Pavement	57.5	16.25	0.80	0.82	
	OFF	Gravel	54.0	18.73	0.61	0.63	n/a

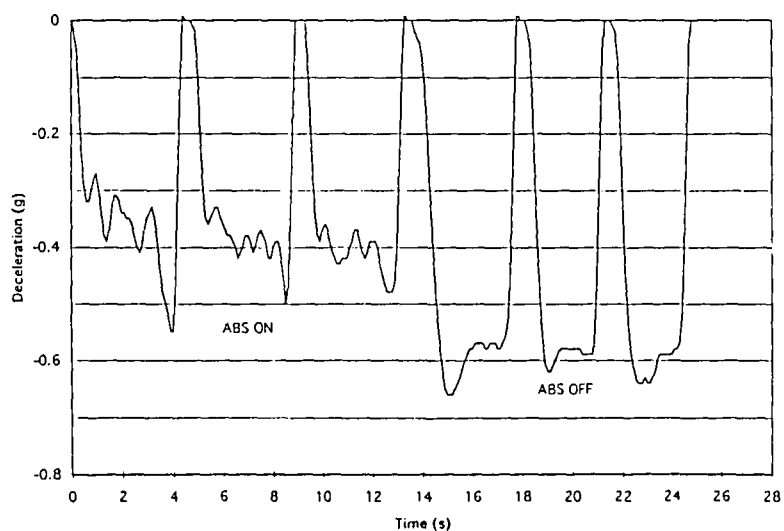
**Table 4.**  
**G-analyst and Vericom Results**

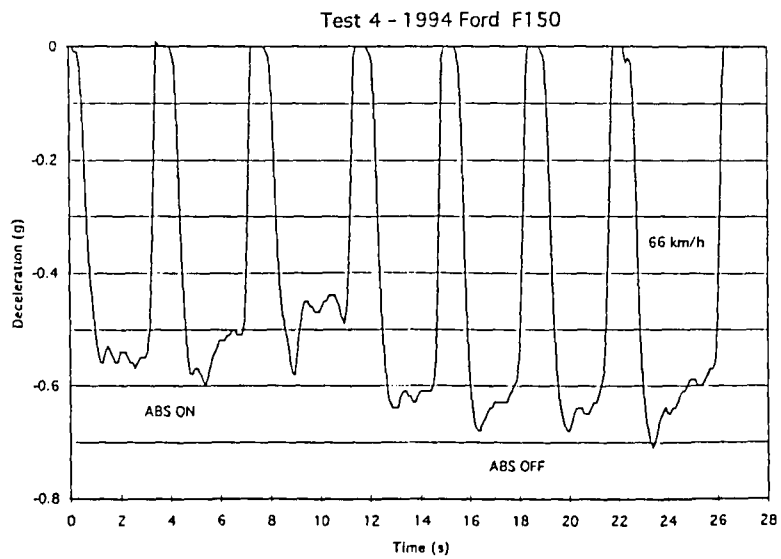
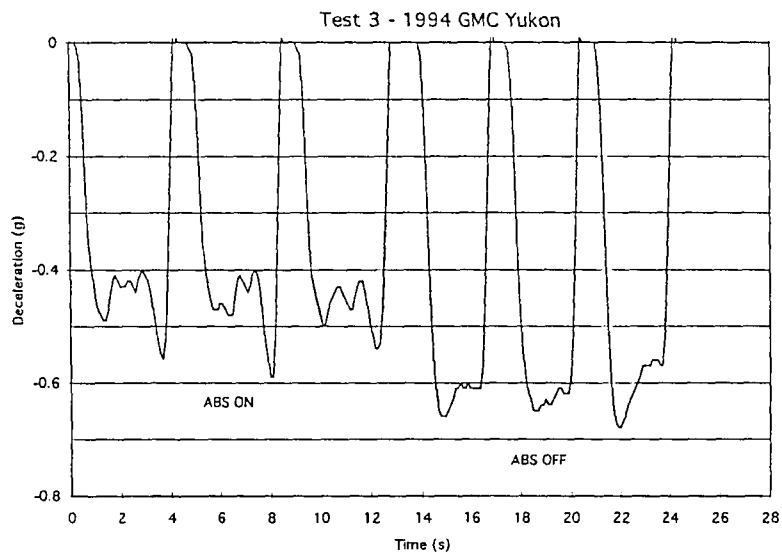
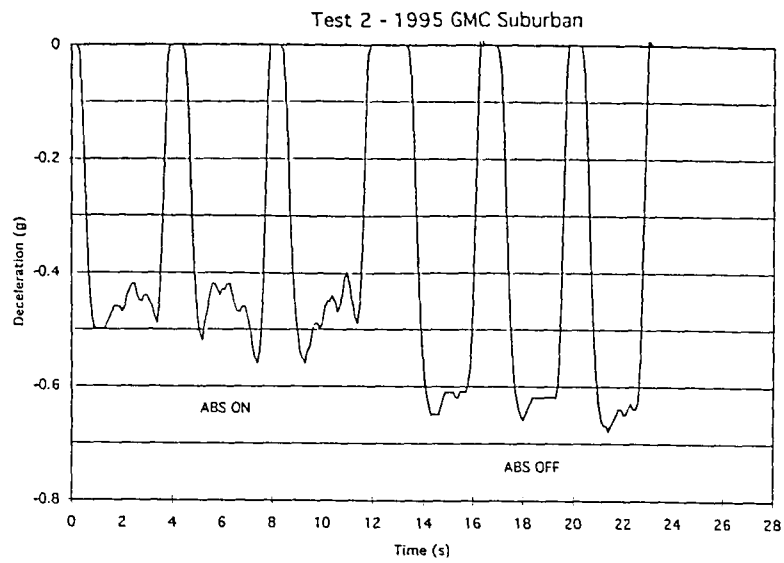
Test Vehicle	ABS	Surface Condition	G-analyst average (g)	% Diff 1- (On/Off)	Vericom average (g)	% Diff 1- (On/Off)
1	ON	Pavement	0.85		0.78	
	ON	Gravel	0.37		0.38	
	OFF	Gravel	0.59	37.3	0.56	32.1
2	ON	Pavement	0.76		0.71	
	ON	Gravel	0.47		0.46	
	OFF	Gravel	0.62	24.2	0.59	22.0
3	ON	Pavement	0.75		0.71	
	ON	Gravel	0.45		0.45	
	OFF	Gravel	0.61	26.2	0.58	22.4
4	ON	Pavement	0.83		0.76	
	ON	Gravel	0.52		0.48	
	OFF	Gravel	0.63	17.5	0.58	17.2
5	ON	Pavement	0.79		0.74	
	ON	Gravel	0.50		0.47	
	OFF	Gravel	0.66	24.2	0.62	24.2
6	ON	Pavement	0.89		0.93	
	ON	Gravel	0.42		0.40	
	OFF	Gravel	0.66	36.4	0.65	38.5
7	OFF	Pavement	0.88		0.83	
	OFF	Gravel	0.63	n/a	0.61	n/a

#### APPENDIX D

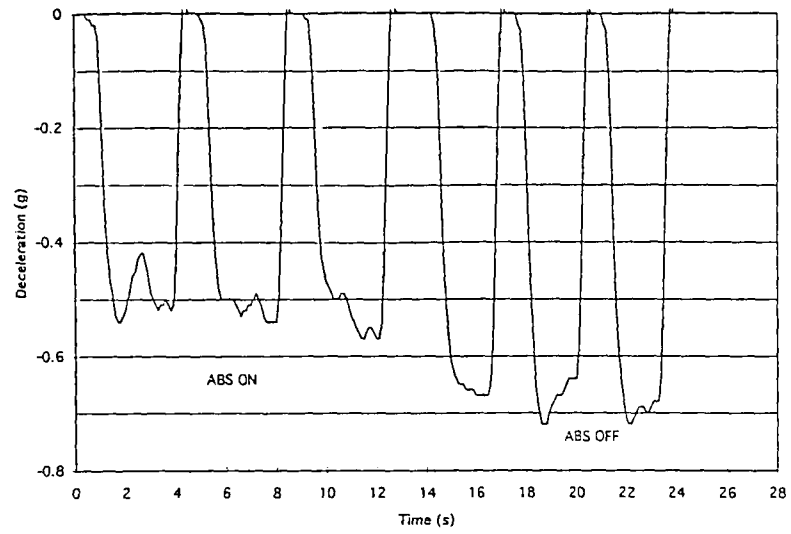
#### G-ANALYST PLOTS OF BRAKING ON GRAVEL SURFACE WITH ABS ON AND ABS OFF

Test 1 - 1993 GMC Suburban

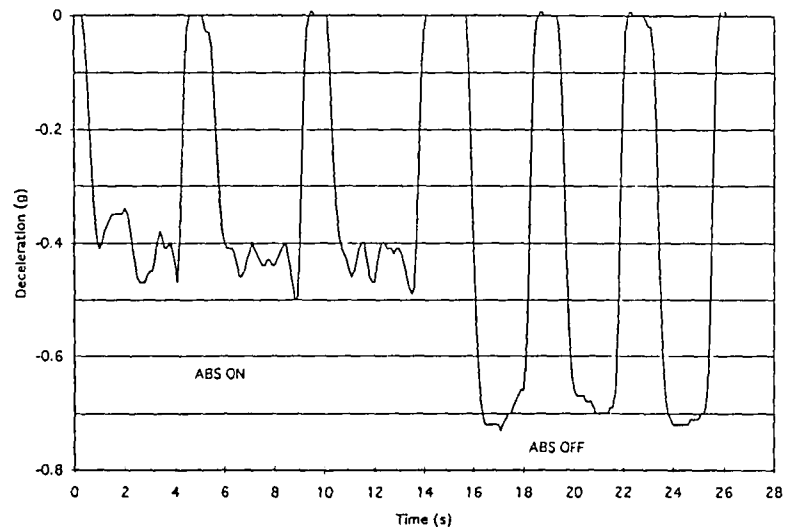




Test 5 - 1993 Ford Explorer



Test 6 - 1996 Chevrolet Cavalier



# Technical Session 3

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## Vehicle Compatibility

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Chairperson: Richard Lowne, Transport Research Laboratory, United Kingdom

The International Harmonized Research Activities (IHRA) Status Report of the Vehicle Compatibility Working Group was presented at the onset of this Session during the 16<sup>th</sup> ESV Conference. This Report begins Technical Session 3.

## INTERNATIONAL HARMONIZED RESEARCH ACTIVITIES (IHRA) STATUS REPORT OF THE VEHICLE COMPATIBILITY WORKING GROUP

**Keith Rodgers**

Department of the Environment Transport and the Regions  
United Kingdom

### INTRODUCTION

At the Melbourne ESV in May 1996, as part of the International Harmonised Research Activities (IHRA), it was agreed that one of the six Working Groups set up was to study compatibility. It was recognised that separate regulations on frontal and side impact do not address compatibility problems. Research programmes on compatibility between cars are now active in a number of countries and it was agreed that international co-ordination on all this work would be beneficial.

The European Union and the European Enhanced Vehicle-Safety Committee were asked to be the lead group for the compatibility work. In turn the United Kingdom was invited to nominate a chairman for the working group. Action was taken in early 1997 to set up the group and define its objectives. Meetings so far have been held in June and October 1997 and in February 1998. The fourth meeting is to take place during the ESV conference in Windsor.

### AIM

The aim of it is to develop internationally agreed test procedures designed to improve the compatibility of car structures in front to front and front to side car to car impacts thus enhancing the level of occupant protection provided in frontal and side impacts. A secondary aim will be to consider the protection in impacts with pedestrians, heavy goods vehicles and other obstacles.

### PARTICIPATION

The EU and EEVC agreed that participation in the IHRA Working Group from within Europe would be limited to the Chairman and Secretary plus two Members from EEVC Working Group 15 which is studying compatibility issues within Europe. In addition to these four, member representatives have also been nominated from the United States, Canada, Australia, Japan, and Poland.

The IHRA Steering Committee meeting in November 1997 agreed that all IHRA Working Groups should have representation from industry. A letter was

sent by NHTSA to OICA in March 1998 inviting them to nominate three Working Group Members from industry to represent North America, Europe and the Far East. It is anticipated that future meetings of the Working Group will include these representatives.

### WORKPLAN

When IHRA was set up in 1996 it was agreed that the aim should be for all work groups to have completed their tasks in time to report to the ESV conference in 2001. With regard to compatibility this is an act of faith as the problems are not simple and require a timely breakthrough if this programme is to be met.

At Annex A shows the work planned which is broken into three main activities:

- **Problem definition.** Real life accidents are the key to defining the compatibility problems that exist today. This work is to study the statistics on fleet make up in various countries as well as the typed of accidents that occur on their roads. It will be necessary to extract from this information accidents where compatibility has had a part to play in the outcome. Once these accidents are identified they can be used to determine the important characteristics for compatibility.
- **Key characteristics.** Once found, these characteristics will be used to replicate real accidents by crash testing, and by system modelling to be able to understand what is happening on the road. By this means it should be possible to develop a hypothesis on compatibility and find out how the effects can be mitigated.
- **Assessment methodology.** The final phase of the workplan is to develop testing protocols which when adopted into regulations will ensure that vehicles become more compatible.

At Annex B shows the tasks that each member has agreed to undertake and the time frame which is being allocated for them to be completed. As it will be seen this predicts a completion of the work activity at year 2000, but as explained there is no clear way to achieving the goals by this date.



## **PROGRESS**

### **Fleet Studies**

The EEVC working group had in place a work task to create a data base of current cars in Europe giving the various parameters for each model that it was thought would influence compatibility. These parameters included such factors as types of structure and the position of stiff elements that would react with one another in accidents. This work is almost complete.

In the USA work had been completed to categorize the vehicle fleet and study how this was changing. A particular problem identified was the number of sport utility vehicles emerging in their market. It became apparent that the size difference between these vehicles and the rapid growth in the proportion of these types of vehicles in the fleet was going to pose a big problem for compatibility.

Elsewhere work on the fleet studies has yet to be reported to the IHRA working group but work has been promised for the future.

### **Accident Studies**

Accident studying in a number of countries in Europe is very mature and ranges from the collection of overall statistics to detailed investigation of specific accidents. Investigations are carried out "on the spot" in some countries whilst in others the work is done post accident. Experts have been assembled to discuss compatibility issues as displayed by current accidents, but as yet no conclusions have been drawn from this work. The intention is to identify types of vehicles that exhibit both good and poor compatibility and then study individual accidents involving these types to obtain information to be taken forward into the "key characteristics" phase.

In the USA work has been completed on studying the compatibility aspect of the existing fleet allowing vehicles to be positioned in a compatibility matrix. Follow up studies using current accident data will continue for the period of the IHRA work.

Elsewhere work has yet to be reported to the IHRA working group.

### **Modelling**

Modelling programmed under the work plan controlled by EEVC WG15 has just started and as yet there is a little output. The intention is to use this work in conjunction with the crash testing programmes. Some finite element models will be obtained through the work in the USA on compatibility and TRL is also using FE models supplied by some manufacturers. The UK is also funding some further modelling effort in this area which will be fed in through WG15.

The USA modelling programme is advanced both in deriving individual models for representative fleet vehicles, as well as in producing a system model of vehicle accident activity in the US. So far no other modelling activity is occurring elsewhere in the programme.

### **Crash Testing**

As yet no crash testing has occurred specifically for IHRA. This activity is about to get under way in the US, but the EEVC work awaits better definition from the accident and modelling studies.

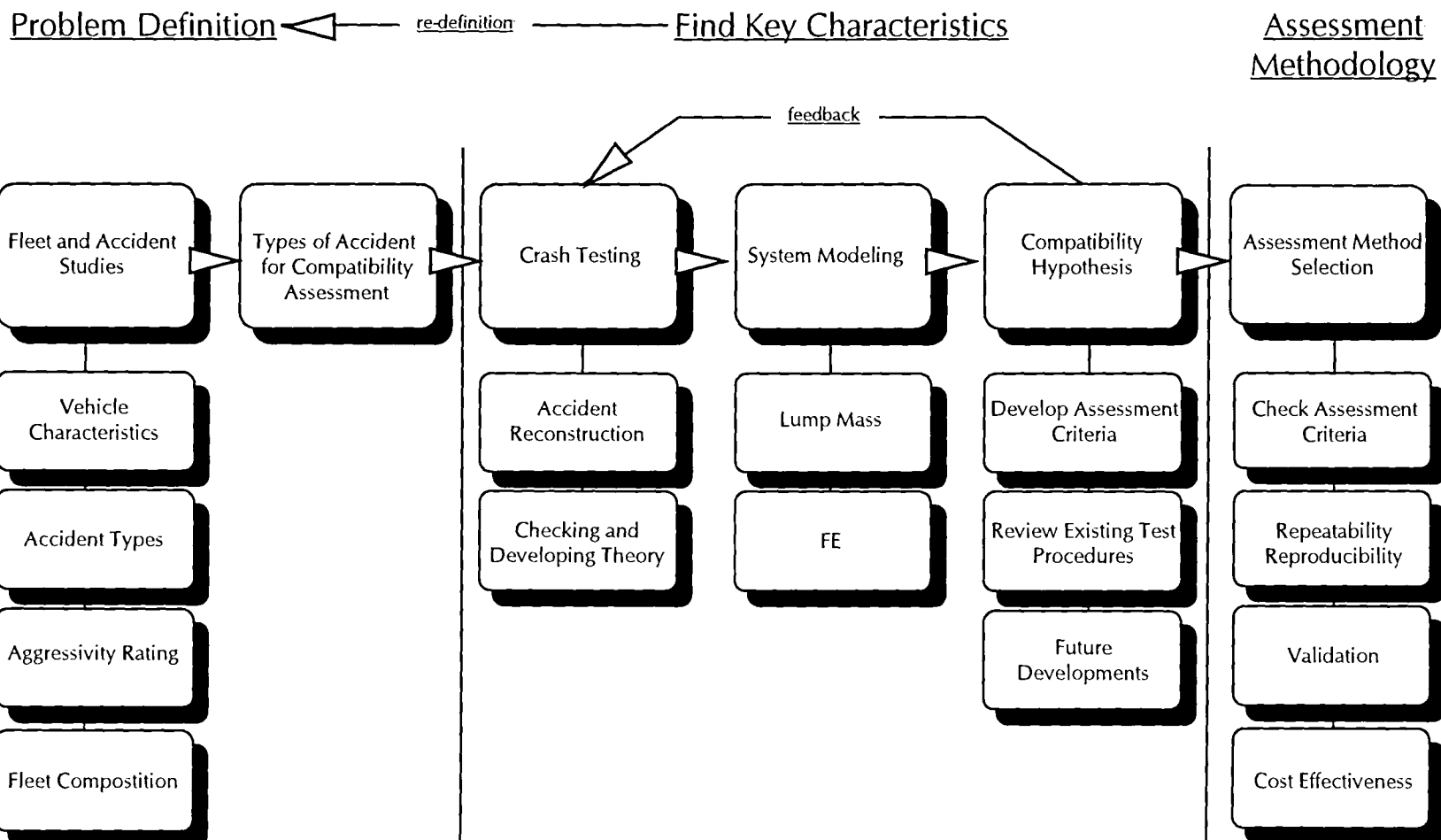
## **CONCLUSIONS**

The IHRA Compatibility working group was set up after work in the area was already underway in several countries. The task of the working group has been to co-ordinate these efforts, and to steer them towards common goals. One of these goals is to have results available by 2001, to achieve this all participants have been encouraged to think now about possible testing methods so that there can be concurrent activities to reduce the overall time frame. A second goal concerns deriving common methods to control compatibility, which takes into account the dissimilar conditions applying on different continents. It is apparent that fleet mix could be an area which poses a problem as the average sizes of vehicles vary dramatically between continents.

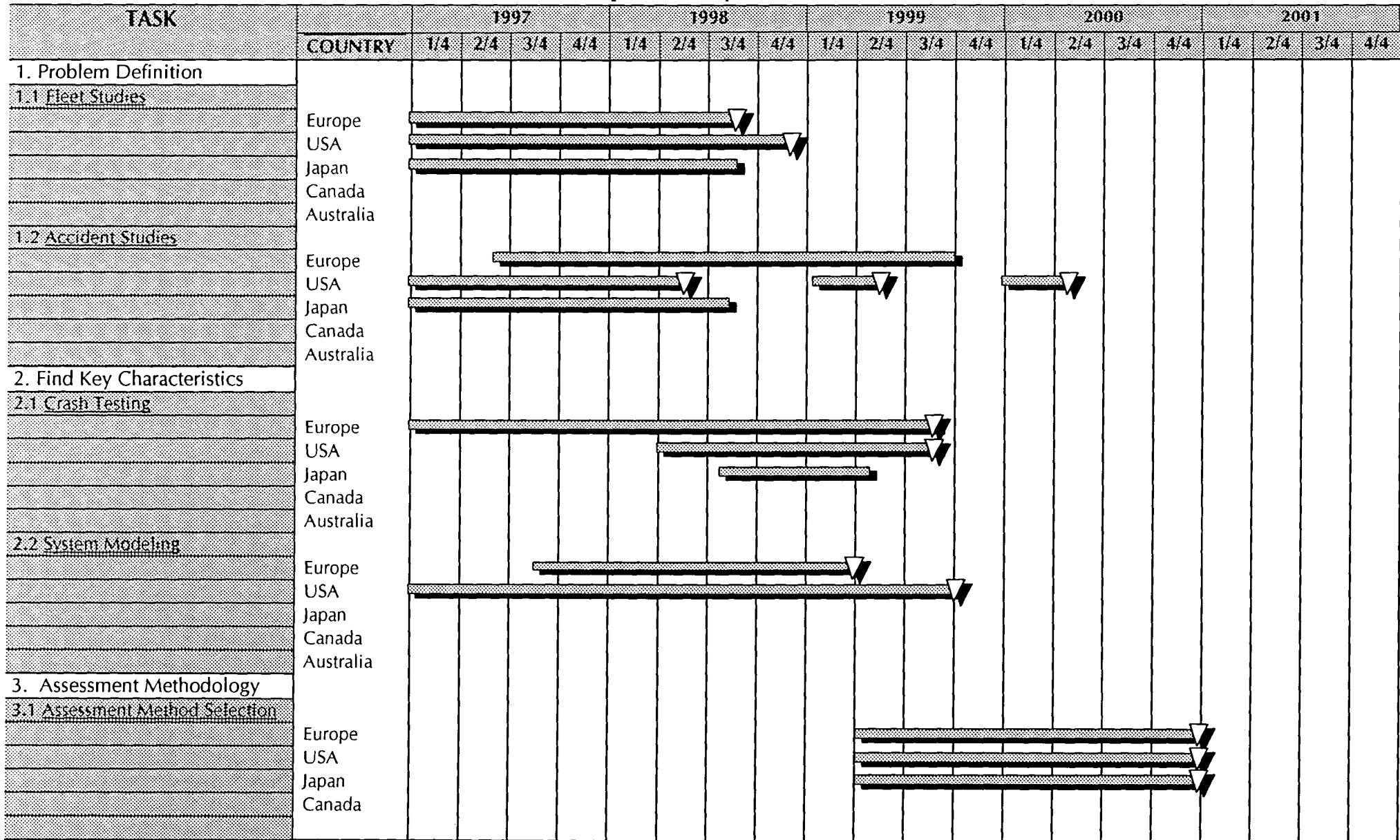
# International Harmonised Research Agenda

## Compatibility Research

Lead Country: EU/EEVC



# Compatibility Research



▼ Deliverable

# NHTSA'S VEHICLE AGGRESSIVITY AND COMPATIBILITY RESEARCH PROGRAM

Hampton C. Gabler

William T. Hollowell

U.S. National Highway Traffic Safety Administration

United States

Paper No. 98-S3-O-01

## ABSTRACT

NHTSA has initiated a research program to investigate the problem of aggressive or incompatible vehicles in multi-vehicle crashes. Collisions between cars and light trucks and vans are one specific, but growing, aspect of this larger problem. Light trucks and vans (LTVs) currently account for over one-third of registered U.S. passenger vehicles. Yet, collisions between cars and LTVs account for over one half of all fatalities in light vehicle-to-vehicle crashes. In these crashes, 81 percent of the fatally-injured were occupants of the car. These statistics suggest that LTVs and passenger cars are incompatible in traffic crashes, and that LTVs are the more aggressive of the two vehicle classes. The availability of newer safety countermeasures, e.g., air bags, appears to improve compatibility indirectly by improving the crashworthiness of later model vehicles. However, the fundamental incompatibility between cars and LTVs is observed even when the analysis is restricted to collisions between vehicles of model year 1990 or later -- indicating that the aggressivity of LTVs will persist even in future fleets. This paper presents an overview of results to date from this research program.

## INTRODUCTION

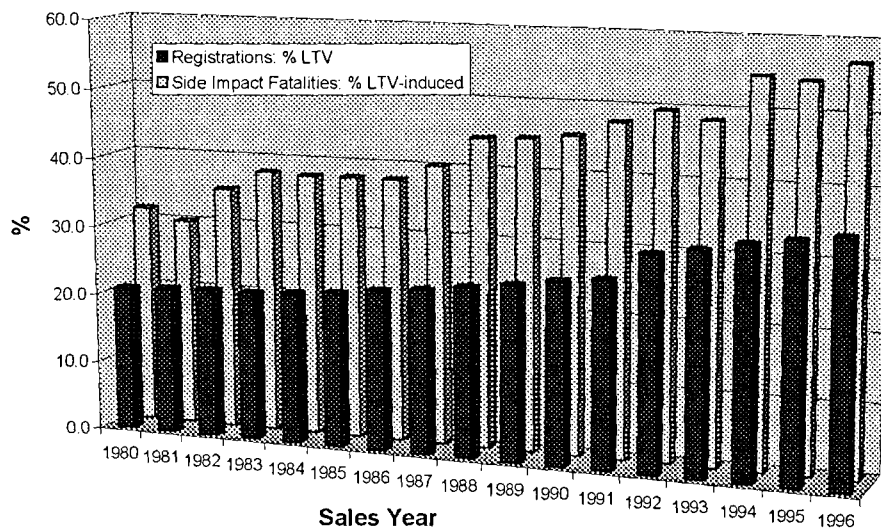
The National Highway Traffic Safety Administration (NHTSA) is conducting a research program to investigate the crash compatibility of passenger cars, light trucks and vans in vehicle-to-vehicle collisions. The compatibility of a vehicle is a combination of its crashworthiness and its aggressivity when involved in crashes with other members of the vehicle fleet. While crashworthiness focuses on the capability of a vehicle to protect its occupants in a collision, aggressivity is measured in terms of the casualties to occupants of the other vehicle involved in the collision. Improvements in crash compatibility may require improvements in crashworthiness coupled with simultaneous reductions in aggressivity.

The near term objective of this program is to identify and demonstrate the extent of the problem of incompatible vehicles in vehicle-to-vehicle collisions. The goal is to identify and characterize compatible vehicle designs with the expectation that improved vehicle compatibility will result in large reductions in crash related injuries. The research effort seeks to identify those vehicle structural categories, vehicle models, or vehicle design characteristics which are aggressive based upon crash statistics and crash test data. LTV-to-car collisions are one specific, but growing, aspect of this larger problem [1,2].

## THE DEMOGRAPHICS OF LTV AGGRESSIVITY

During the past decade, a profound shift in the composition of the passenger vehicle fleet has been realized in the U.S.. Fueled by the growing popularity of pickup trucks, minivans, and, more recently, by sports utility vehicles, the demographics of the U.S. fleet are characterized by a growing population of light trucks and vans (LTVs). As a group, LTVs are heavier, of more rugged construction, and have higher ground clearance than the passenger cars with which they share the road. The concern is that these design features, introduced to allow specialized functions e.g. off-road driving, may make LTVs fundamentally incompatible with cars in highway crashes, and in some cases dangerous to the occupants of cars struck by LTVs.

As shown in Figure 1, registrations of LTVs currently account for over 1/3 of all light vehicle registrations (Polk, 1980-1996), and are a growing component of the U.S. fleet. During the period from 1980 to 1996, LTV vehicle registrations increased from 20 percent to 34 percent. Although LTVs only account for 1/3 of all registered vehicles, traffic crashes between an LTV and any other light vehicle now account for the majority of fatalities in vehicle-to-vehicle collisions. As shown in Table 1, in 1996 LTV-car crashes accounted for 5,259 fatalities while car-car crashes led to 4,013 deaths and LTV-LTV crashes resulted in 1,225 fatalities.



**Figure 1. LTV Registrations vs. LTV-induced Side Impact Fatalities.**  
 (Based on U.S. Light Truck and Van Registrations as a fraction of light vehicle registrations, R.L. Polk Co., 1980-96, and Side Impact Fatalities resulting from LTVs striking passenger cars and other LTVs as a fraction of total side impact fatalities, FARS 1980-96).

Year	All car-car	All LTV-car	All LTV-LTV	Total
1980	6506	3580	510	10596
1981	6510	3292	482	10284
1982	5437	3452	556	9445
1983	5157	3408	505	9070
1984	5340	3540	593	9473
1985	5174	3608	635	9417
1986	5450	3895	660	10005
1987	5489	4277	788	10554
1988	5320	4676	802	10798
1989	5175	4730	861	10766
1990	4726	4719	867	10312
1991	4482	4297	873	9652
1992	4208	4421	804	9433
1993	4364	4451	977	9792
1994	4219	4972	1059	10250
1995	4097	5238	1183	10518
1996	4013	5259	1225	10497

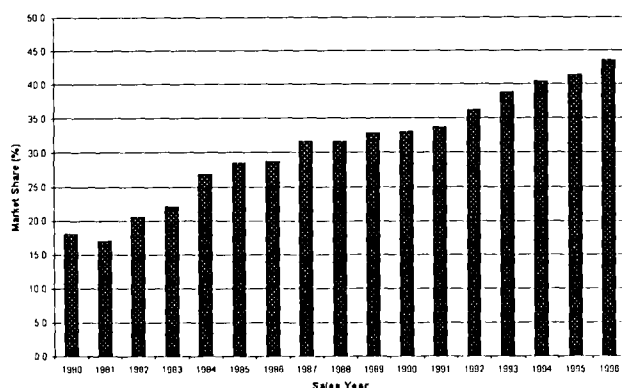
**Table 1. Fatalities in Light Vehicle-to-Vehicle Crashes**

Year	Car into Car	Car into LTV	LTV into Car	LTV into LTV	Total
1980	2071	170	962	78	3281
1981	2077	161	876	87	3201
1982	1881	174	1015	102	3172
1983	1848	190	1134	118	3290
1984	1996	153	1186	122	3457
1985	1943	178	1168	130	3419
1986	2149	192	1285	147	3773
1987	2121	246	1382	216	3965
1988	2026	262	1645	194	4127
1989	2144	231	1697	238	4310
1990	1976	255	1628	234	4093
1991	1812	216	1614	232	3874
1992	1705	252	1698	223	3878
1993	1759	224	1609	256	3848
1994	1667	229	1983	318	4197
1995	1749	237	2049	316	4351
1996	1613	276	2181	314	4384

**Table 2. Light Vehicle-to-Vehicle Side Impacts: Fatalities in Side-Struck Vehicle**

Year	Car-Car	Car-LTV (LTV Fatal)	Car-LTV (car Fatal)	LTV-LTV	Total
1980	3395	521	1254	303	5473
1981	3331	422	1208	278	5239
1982	2731	463	1197	330	4721
1983	2465	400	1115	283	4263
1984	2515	434	1159	351	4459
1985	2420	415	1217	362	4414
1986	2440	461	1289	373	4563
1987	2493	483	1407	404	4787
1988	2398	487	1498	437	4820
1989	2238	481	1478	446	4643
1990	2056	500	1538	450	4544
1991	1964	437	1321	432	4154
1992	1857	448	1282	418	4005
1993	1899	439	1460	543	4341
1994	1956	442	1548	521	4467
1995	1692	510	1658	656	4516
1996	1776	453	1529	651	4409

**Table 3. Fatalities in Light Vehicle-to-Vehicle Frontal Impacts**



**Figure 2. U.S. Sales of LTVs from 1980-1996 expressed as a fraction of light vehicle market share (Automotive News Market Data Book).**

A disproportionate number of the fatalities in LTV-car crashes are incurred by the car occupants. Of the 5259 fatalities in LTV-car crashes in 1996, 81 percent of the fatally-injured were occupants of the car. As shown in Figure 1 and tabulated in Table 2, side impacts in which an LTV was the bullet vehicle led to 56.9 percent of all fatalities in side struck vehicles. As shown in

Table 3, in 1996, frontal impacts in which an LTV was involved accounted for 2633 deaths (or 59.7%) of the 4409 fatalities in frontal impact in that year.

These statistics suggest that LTVs and passenger cars are incompatible in traffic crashes, and that LTVs are the more aggressive of the two vehicle classes. In particular, crashes with an LTV cause a disproportionate number of vehicle-to-vehicle fatalities.

Fatalities and injuries which arise from the incompatibility of LTVs and cars is a growing problem. As shown in Figure 2, LTV market share has risen steadily from 1980 to 1996 [2]. LTVs captured over 43 percent of all light vehicle sales in 1996. Comparison of LTV registrations and LTV-caused fatalities over the same period show that LTV impacts have always caused a disproportionate number of vehicle-to-vehicle fatalities. For example in 1980, LTVs accounted for 20 percent of the registered light vehicle fleet, but side impacts in which an LTV was the bullet vehicle led to 31 percent of all fatalities in side struck vehicles. The magnitude of this problem then is not only due to the aggressivity of LTVs in crashes, but also the result of the dramatic growth in the LTV fraction of the U.S. fleet.

## PROBLEM DEFINITION

The research program examined U.S. crash statistics to determine the characteristics and extent of the vehicle compatibility problem. One obstacle to quantifying the compatibility of a vehicle is the lack of an accepted measure of compatibility. A primary objective of our research effort was to develop a clearly defined metric for measurement of vehicle aggressivity. To date, the NHTSA aggressivity research program has developed two potential aggressivity metrics.

### Option 1:

$$Aggressivity = \frac{\text{Fatalities in collision partner}}{\text{Registrations of subject vehicle}}$$

### Option 2:

$$Aggressivity = \frac{\text{Driver Fatalities in collision partner}}{\text{Number of Crashes of subject vehicle}}$$

The first metric was used in our early Aggressivity research as reported at the 15<sup>th</sup> ESV conference [2]. For each vehicle make / model, this metric determines the number of fatalities in the collision partner resulting from collisions with the subject vehicle. Only two-vehicle crashes in which both vehicles were either a car or an

LTV are considered. The fatality count is normalized by the total number of registrations of the subject vehicle so that vehicles with large populations are not unfairly penalized. Using this metric, the U.S. fleet was rank ordered by aggressivity as presented at the 15<sup>th</sup> ESV conference. This initial study indicated that LTVs as a group were twice as aggressive in crashes as passenger cars -- i.e., per vehicle, LTVs caused more than twice as many fatalities in their collision partners as do cars.

The second, more recent, metric represents a refinement to the earlier definition of aggressivity. The second metric defines aggressivity to be the number of driver fatalities in the collision partner normalized by the number of vehicle-to-vehicle crash involvements of the subject vehicle. Only two-vehicle crashes in which both vehicles were either a car or an LTV are considered in computing the fatality count and the crash involvement count. One of the confounding factors in determining aggressive vehicle designs is aggressive driver behavior. Because aggressive drivers are involved in more crashes than less aggressive drivers, normalizing by the number of crashes rather than vehicle registrations focuses the metric more on vehicle performance and less on driver behavior. Note also that the second metric keys on driver fatalities rather than all fatalities in the struck vehicle. Because all vehicles have only one driver, this refinement avoids any biases accruing from differences in vehicle occupancy rate between, for example, pickup trucks and minivans.

## Approach

The analysis for the second metric used statistics from the Fatality Analysis Reporting System (FARS) to determine the number of fatalities, and statistics from the General Estimates System (GES) to determine the number of crash involvements. FARS provides a comprehensive census of all U.S. traffic related fatalities. GES is a large sample of over 60,000 police reported crashes collected annually. The scope of our analysis was constrained to cars, light trucks, and vans under 10,000 pounds in Gross Vehicle Weight Rating (GVWR). The focus was further narrowed to two vehicle collisions in which the vehicles were either cars or LTVs. The fatality counts in the struck vehicle were limited to driver fatalities.

Note that because GES is a sample of police-reported crashes, estimates from GES are subject to both sampling and nonsampling errors [9]. Initial analysis of GES revealed that approximately half of the make and model codes in this database were listed as unknown. For those GES cases with valid Vehicle Identification Numbers (VINs), the make and model was obtained by decoding the VIN using a combination of the VINDICATOR code, developed by the Highway Loss Data Institute, and the

VINA code, developed by the R.L. Polk Company [4]. However, even after decoding the VINs, approximately 20 percent of all vehicle make and models remained unknown. The number of crash involvements for all vehicles was weighted accordingly in order to preserve the total number of crashes. Although this strategy maintains the total count of crash involvements, this approach has the disadvantage of preserving any reporting biases. An improved approach would be to explore the missing data as a function of vehicle body type and model year, and prorate unknown make-models within these categories if biases exist.

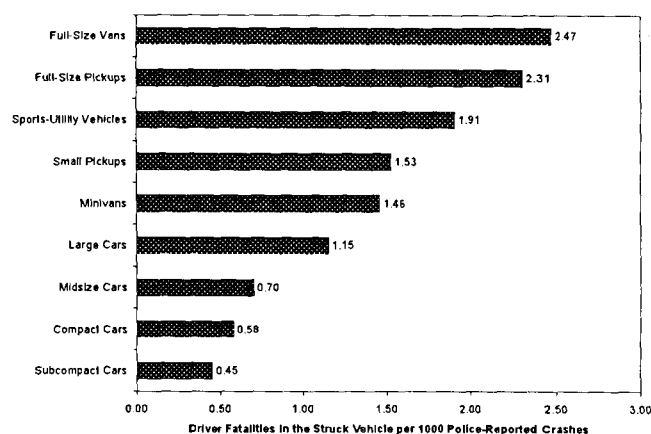


Figure 4. Vehicle Aggressivity by Vehicle Category (FARS/GES 1991-94).

## Overall Fleet Aggressivity Ranking

The second metric, hereafter referred to as the aggressivity metric (AM), was used to rank order all passenger vehicles, cars and LTVs, by their relative aggressivity using 1991-94 FARS and GES. Only current production vehicles with at least 10,000 police-reported crashes over the period of 1991-94 were included in the ranking. The vehicles in the aggressivity ranking was aggregated by vehicle family into five categories of LTVs -- sports utility vehicles, full-sized pickups, small pickups, minivans, and full-sized vans -- and four categories of passenger cars -- large, midsize, compact, and subcompact. The categories assigned to each vehicle were as tabulated in the Automotive News Market Data Book [3]. This study grouped luxury, near luxury, and large cars into a single large car category.

As shown in Figure 4, full-sized vans were found to be the most aggressive vehicle category with an AM = 2.47. This category was closely followed by Full-Size Pickups (AM=2.31), Sports-Utility Vehicles (AM = 1.91), and small pickups (AM = 1.53). Minivans were the least aggressive of all LTV groups with an average

AM = 1.46. The AM of passenger cars was significantly lower and ranged from AM= 0.45 for subcompacts to AM=1.15 for large cars.

Vehicle weight is not always the overriding factor dictating aggressivity as clearly demonstrated by Figure 4. Mid-sized cars, e.g., the Ford Taurus, and the small pickups, e.g., the Ford Ranger, both have approximately the same curb weight of 3,000 pounds. However, small pickups (AM = 1.51) are over twice as aggressive as mid-sized cars (AM = 0.70). The higher aggressivity of the small pickup class may be due to its greater structural stiffness and its higher ride height.

Among cars, the Aggressivity Metric is a strong function of vehicle weight. AM for the large car category, e.g., the Ford Crown Victoria, is 1.15. This is two to three times higher than the AM for the subcompact car category, e.g., Geo Metro, which is 0.45. The conservation of momentum in a collision places smaller cars at a fundamental disadvantage when the collision partner is a heavier vehicle. The importance of car size in providing occupant protection has been demonstrated in several studies of the U.S. crash statistics [5,6].

#### Aggressivity by Impact Mode.

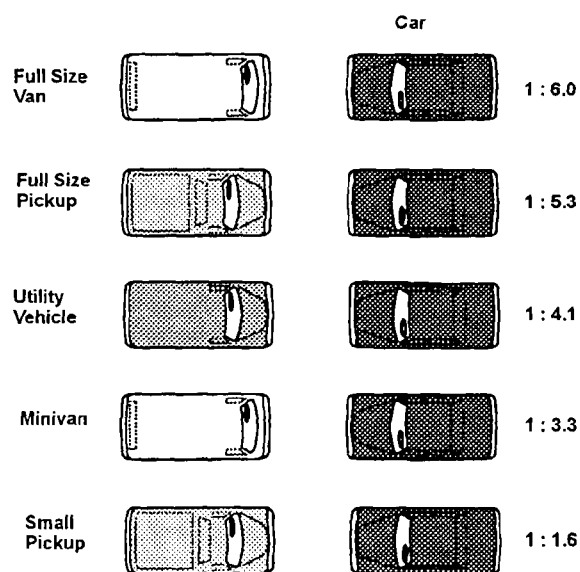
Having established that LTVs are incompatible with cars in traffic crashes, the next requirement was to determine the relationship between aggressivity and impact direction. The analysis computed the ratio of driver fatalities in the subject vehicle vs. driver fatalities in the collision partner for cars versus each of five LTV categories: full-size vans, minivans, utility vehicles, small pickup trucks and full-size pickup trucks. The counts of fatalities were obtained from 1992-96 FARS. All occupant restraint conditions, i.e., belts, air bags, and no restraints, were included.

As noted by Jokschi [7], driver age has a strong effect on the evaluation of crashworthiness and aggressivity. Younger drivers are more injury tolerant and, therefore, less likely to die from their injuries. In contrast, older drivers are less injury tolerant, and are less likely to die from their injuries. Using the approach developed by Jokschi, the results presented below were corrected for the bias which would be introduced by differences in age between the two colliding drivers by restricting the analysis to cases in which both drivers were of age 26-55.

It should be noted in the discussion which follows that this analysis was based on small numbers of fatal crashes (on the order of a hundred for each case), and the results should be regarded as preliminary. For example, in the case of minivans striking cars in side impact, the ratio of 16:1 was determined based upon 106 fatalities in the car versus 7 fatalities in the minivan. For this

particular case, note that small changes in the number of minivan fatalities would make large differences in the fatality ratio.

The ratio of driver fatalities in the subject vehicle to driver fatalities in its collision partner driver resulting from frontal-frontal impacts is presented in Figure 5. In collisions between full-size vans and cars, 6 drivers died in the car for every driver who was killed in the van. In collisions between full-size pickup trucks and cars, 5.3 drivers died in the car for every driver who was killed in the pickup. In collisions between utility vehicles and cars, 4.1 drivers died in the car for every driver who was killed in the utility vehicle. Clearly, the fatality toll in car-LTV frontal crashes is disproportionately shouldered by the drivers of passenger cars.



**Figure 5. Ratio of Fatally-Injured Drivers in LTV-to-Car Frontal Collisions. FARS 1992-96.**

The ratio of striking-to-struck driver fatalities resulting from side impacts are presented in Figure 6. This analysis includes both left and right side impacts. As a control configuration, note first that in car-to-car impacts approximately 6 side-struck drivers are fatally injured for every fatally-injured driver in the bullet car. This imbalance is not unexpected as the side structure of passenger vehicles provides little protection for the side-struck occupant when compared with the significantly greater protection afforded by the front structure to the bullet vehicle driver.

The analysis is even more startling for LTVs striking cars in side impact. As shown in Figure 6, 23 side-struck car drivers are fatally injured for every driver who dies in a striking full-size van. For every driver who dies in a



striking utility vehicle, 20 side-struck car drivers are fatally injured. For every fatally-injured driver of a striking full-size pickup truck, 17 side-struck car drivers are killed.

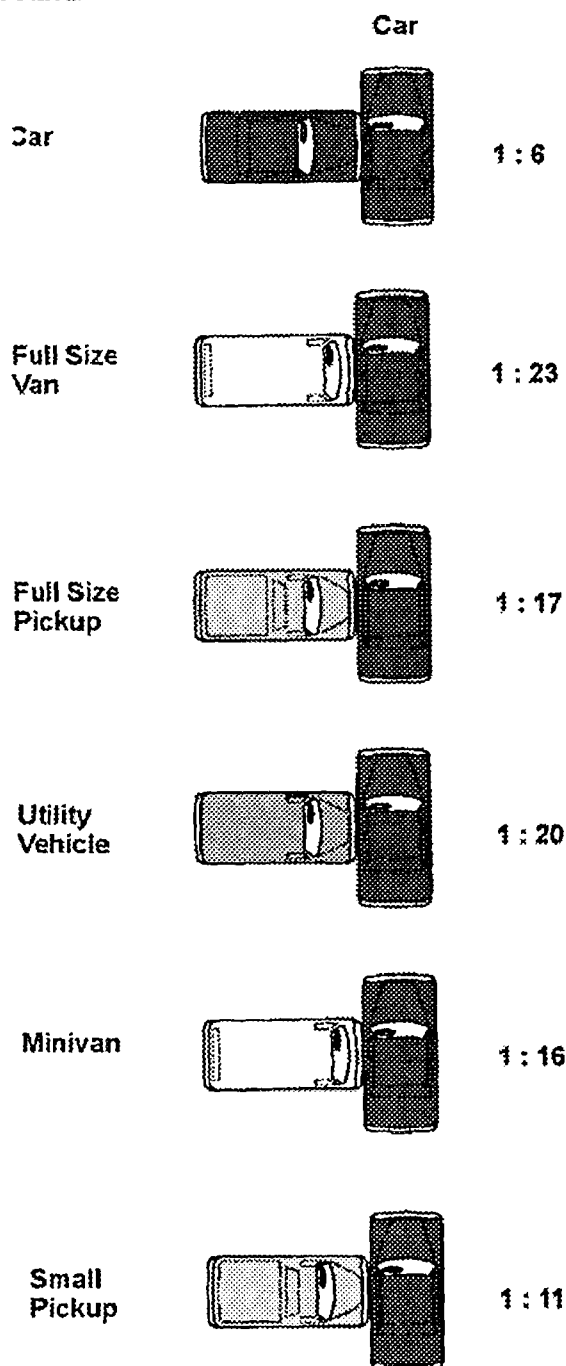


Figure 6. Ratio of Fatally-Injured Drivers in LTV-to-Car Side Impacts. FARS 1992-96.

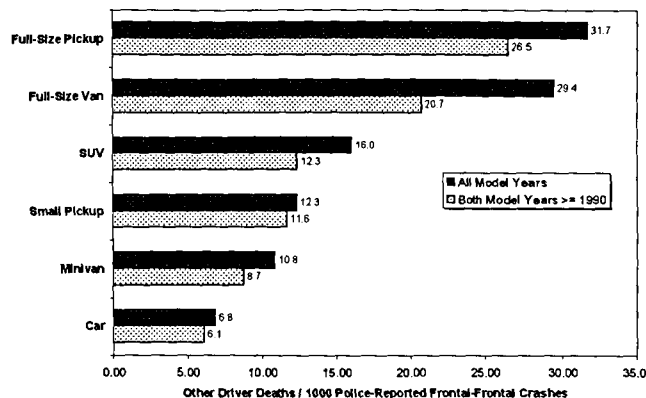


Figure 7. Aggressivity by Vehicle Category in Frontal-Frontal Impacts. (1992-96 FARS and GES)

#### Aggressivity in Future Fleets

The previous analyses have examined crash compatibility in vehicle-to-vehicle collisions between cars, light trucks and vans in the current fleet, and included all model years. Recent model year cars and LTVs however have safety countermeasures, e.g., air bags which were not available in earlier models, but will be a standard component of future fleets. To understand the nature of aggressivity of light trucks and vans in future fleets, the preceding analyses were repeated for vehicle-to-vehicle collisions in which both vehicles were of model year 1990 or later.

Because a filter of this type sharply restricts the number of cases available for analysis, sufficient numbers were not available to compute meaningful fatality ratios. However, sufficient counts were available for calculation of the Aggressivity Metric presented earlier. The analysis presented below were based on 1992-96 FARS and GES for frontal vehicle-to-vehicle collisions in which both vehicles were either a car or LTV of model year 1990 or later. Note that by examining frontal impacts only, the analysis focuses on the effect of widespread air bag availability in future fleets.

Figure 7 presents aggressivity by vehicle category for all frontal-frontal collisions (no restriction on model year), and for frontal-frontal collisions in which both vehicles were of model year 1990 or later. Comparing the two aggressivity rankings, with and without the model year restriction, the first observation is that, for the late model fleet, the aggressivity metric is lower for all vehicle categories. This is presumably due more to the availability of airbags in the struck vehicle than due to any reduction in aggressivity in the striking vehicle. The second observation is that, despite a reduction in the aggressivity metric in the later model fleet, in every case

LTVs were more aggressive as a group than were cars. The conclusion is that, even with an airbag-equipped late model fleet, there persists a fundamental incompatibility between cars and LTVs in frontal impacts.

### WHY ARE LTVs MORE AGGRESSIVE?

The preceding analysis of crash statistics has clearly demonstrated the incompatibility between cars and LTVs in highway crashes. Still remaining to be determined however are the design characteristics of LTVs which lead to their incompatibility with cars. In general, crash incompatibility arises due to the three factors:

- Mass Incompatibility.
- Stiffness Incompatibility
- Geometric Incompatibility.

The following section will examine the relationship between LTV-car compatibility and these sources of incompatibility.

#### Mass Incompatibility

LTVs are 900 pounds heavier than cars on average [6]. The conservation of momentum in a collision places smaller vehicles at a fundamental disadvantage when the collision partner is a heavier vehicle. As shown in Figure 8, LTVs, as a group, tend to be heavier than passenger cars [8]. Figure 8 crossplots AM as a function of vehicle weight, and demonstrates the relationship between mass and aggressivity.

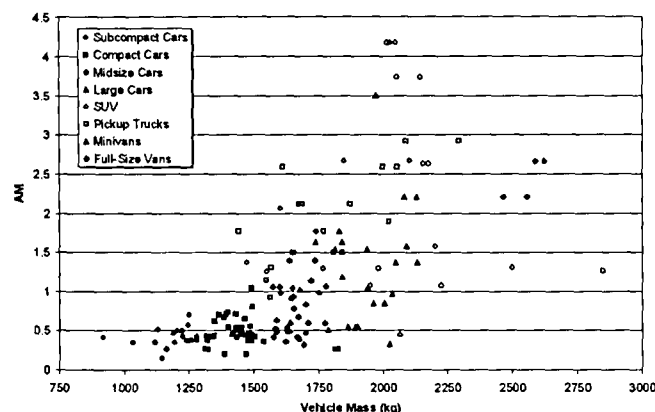


Figure 8. Aggressivity as a function of Vehicle Mass.

#### Stiffness Incompatibility

As a group, LTV frontal structures are more stiff than passenger cars. LTVs frequently use a stiff frame-rail design as opposed to the softer unibody design favored for cars. Drawing on NHTSA New Car

Assessment Program crash test results, the linear stiffness of a selection of LTVs and cars was estimated using the following relationship:

$$k = (mv^2) / x^2 \text{ (Eqn. 1)}$$

where  $m$  is the mass of the vehicle,  $v$  is the initial velocity of the vehicle, and  $x$  is the maximum dynamic crush of the vehicle. The relationship between linear stiffness and AM is shown in Figure 9. Figure 9 indicates that stiffness is a contributing factor to the aggressivity of a vehicle. Because the stiffness of a vehicle is also somewhat related to its mass, as shown in Figure 10, stiffness may not prove to be as dominant an aggressivity factor as mass. Although stiffness and mass are related in many cases, stiffness is not totally driven by the mass of the vehicle. Figure 10 shows that for any given mass, there is a wide distribution of linear stiffness values. For example for 1750 kg vehicles, the least stiff vehicles are passenger cars while the most stiff vehicles are LTVs.

Figure 11 compares the frontal stiffness of a Ford Taurus and a Ford Ranger pickup. Both vehicles have approximately the same mass, but note that the Ranger pickup is significantly stiffer than the Taurus. In a frontal collision between the two, the bulk of the crash energy would be absorbed by Taurus and the Taurus occupants. Far less energy would be absorbed by the Ranger. From a compatibility perspective, a more ideal scenario would be for the Taurus and Ranger structures to each share the crash energy rather than forcing one of the collision partners to absorb the bulk of the crash.

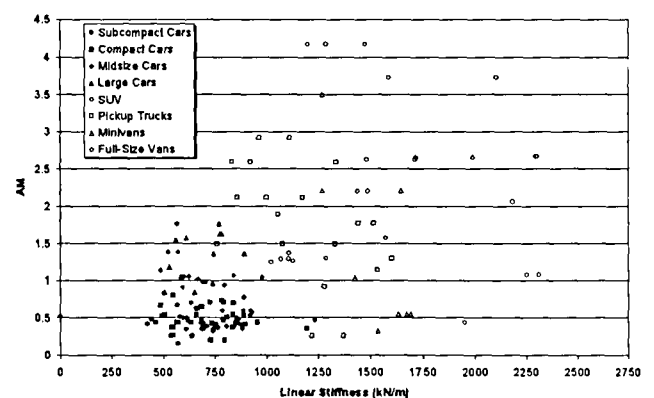
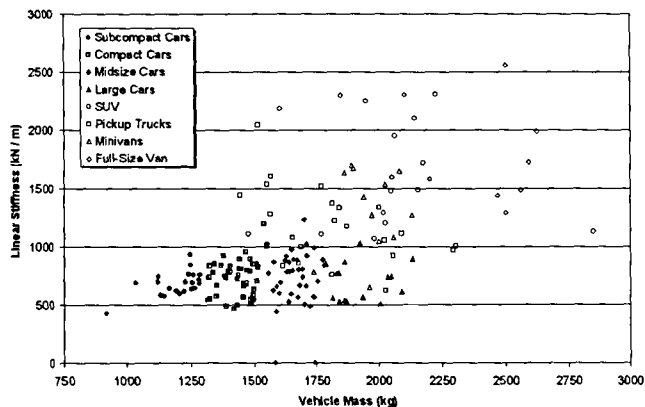
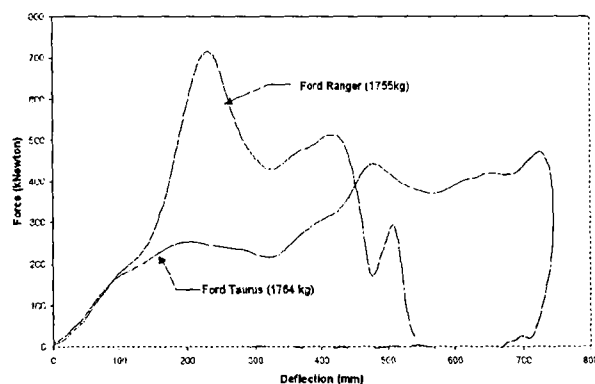


Figure 9. Aggressivity as a Function of Linear Stiffness as computed from NCAP crash test results.



**Figure 10. Relationship between Frontal Stiffness and Vehicle Mass as determined from NCAP Crash Tests.**



**Figure 11. Frontal Stiffness: Small Pickup (Ford Ranger) vs. Midsize Car (Ford Taurus)**

### Geometric Incompatibility

LTVs, especially four-wheel drive sport utility vehicles, ride higher than cars. This creates a mismatch in the structural load paths in frontal impacts, and may prevent proper interaction of the two vehicle structures in a collision. In a side impact, this imbalance in ride height allows the LTV structure to override the car door sill, and contributes to the intrusion of the side-impacted vehicle.

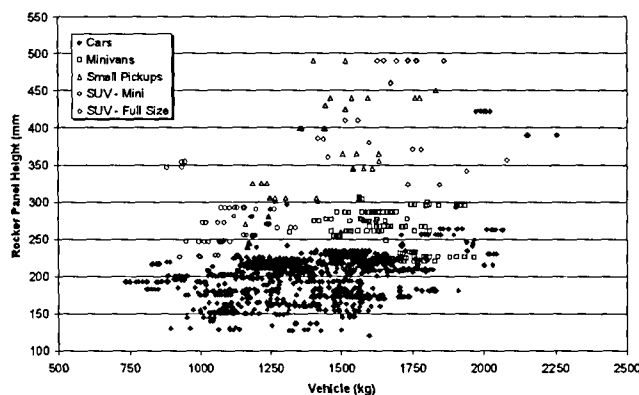
Ideally, the ride height used in an analysis of this type would be the height of the forward-most load bearing structural member of the vehicle. The location of this forward-most structural element however has no precise definition, and must be estimated from other measurements. Some analyses have used bumper height as the height of this load bearing member. However, because in the U.S., the bumper must only meet a 2-1/2 mile/hour bumper impact standard, and LTVs have no

bumper standard, our belief is that, with respect to occupant protection, bumpers are largely ornamental, and their location provides little evidence of the location of load bearing members. The rocker panel, on the other hand, is a much more substantial structural member, and because the rocker panel is typically lower than the forward-most structure, serves as a superior lower bound on the location of the frame structure.

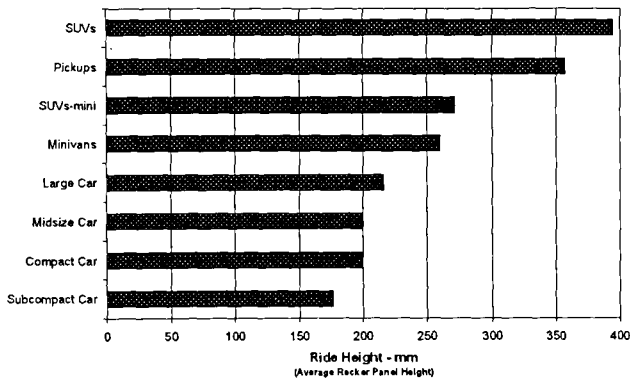
Figure 12 shows that ride height is related somewhat with vehicle mass. For this analysis, ride height is defined to be the ground clearance to the bottom trailing edge of the front wheel well [8]. However note that the rocker panel height across all masses of passenger cars is relatively consistent – perhaps due to the bumper standard with which all passenger cars must comply. On the other hand, LTVs, which have no bumper standard, exhibit a wide variation in ride height and are in general much higher than passenger cars.

Figure 13 presents average ride height by vehicle category. Sport utility vehicles have the highest ride height with an average rocker panel height of 390 mm. Subcompact cars have the lowest-riding height with an average rocker panel height of 175 mm. SUVs ride almost 200 mm higher than mid-sized cars – a geometric incompatibility that would readily permit the SUV to override any side structure in a car and directly strike the car occupant.

It should be noted that the data for the preceding analysis was drawn from AAMA Vehicle Specification Sheets supplied by vehicle manufacturers, and collected in the NHTSA Vehicle Attributes Database [8]. While geometric data was available for most passenger car models, the Vehicle Specification sheets for LTVs was much more limited. The LTV data presented here was primarily obtained from foreign manufacturers, and contains no data on full-sized pickups or vans.



**Figure 12. Relationship between Vehicle Mass and Ride Height as estimated by Rocker Panel Height. Reference: AAMA Vehicle Specification Sheets (1990-94).**



**Figure 13. Geometric Compatibility: Average Ride Height vs. Vehicle Category as determined from AAMA Vehicle Specification Sheets (1990-94).**

## DISCUSSION

The study presented in this paper based its measure of aggressivity upon fatalities per 1000 police reported crashes. No effort was made to control for the severity of the crashes as this information is not available in the GES files. Some make-model vehicles, such as high performance sports cars, may have more severe crashes more because of the driver than because of the vehicle structure. Normalizing fatalities by number of crash involvements removes much of this driver aggressivity effect but does not completely eliminate this effect. Future work will explore refinements to the aggressivity metric which account for crash severity in addition to crash frequency.

The aggressivity metric used in this study assumes that all make-models strike the same cross-section of the vehicle population, i.e., the same proportion of small cars, large cars, minivans, pickups, and so forth. The influence of this assumption upon the aggressivity ranking will be explored in future work. Joks [7] has noted that the age distribution of struck drivers varies somewhat from make-model to make-model. As injury tolerance is a strong function of age, his analysis suggests an additional refinement to the aggressivity metric which corrects for any differences in age distribution from vehicle model to model.

The crash statistics presented in this paper demonstrate a clear incompatibility between cars and LTVs. A comparison of mass distribution, stiffness distribution, and ride height geometry confirm that these two categories of vehicles are incompatible from a design point-of-view. However, this study has not attempted to assign what proportion of the aggressivity of LTVs is a function of each of these three separate sources of incompatibility. To determine the relationship between LTV design features and crash

aggressivity, NHTSA plans to conduct a series of LTV-to-car crash tests in conjunction with a series of finite element simulations of LTV-to-car crash events.

## FUTURE WORK

Compatibility between light trucks and cars is one aspect of a larger study at NHTSA on improving crash compatibility between all categories of light passenger vehicles. Improvements in crash compatibility, in general, and between light trucks and cars, specifically, will likely require design modifications to the struck vehicle, to improve its crashworthiness, as well as to the striking vehicle to reduce its aggressivity. This paper has reported on problem definition based upon U.S. crash statistics. Follow-on work is underway or planned which will expand upon these initial analyses as a precursor to potential rulemaking in this area. Specific tasks include:

- Crash Testing.** To demonstrate and better understand the nature of the compatibility problem, in general, and the LTV aggressivity problem specifically, NHTSA is currently conducting a series of crash tests in which a mid-sized car is impacted by (1) a small pickup, (2) a sports-utility vehicle, (3) a minivan, and (4) another mid-sized car. Both frontal-side and frontal-frontal impact modes will be investigated for a total of eight tests.
 

These crash test results will be coupled with the results of detailed finite element simulations to suggest design enhancements necessary to improve compatibility. The results of this study may also serve as the foundation to determine directions for any potential rulemaking in this area. Additional tests will be conducted based on results of the first test series.
- Simulation and Systems Modeling.** This task will develop a large scale systems model which will evaluate vehicle crashworthiness based on the safety performance of the vehicle when exposed to the entire traffic accident environment, i.e., across the full spectrum of expected collision partners, collision speeds, occupant heights, occupant ages, and occupant injury tolerance levels. The foundation for the Systems model will be a comprehensive suite of finite element models and articulated mass models constructed to represent nine light vehicle categories -- five LTV and four passenger car -- and their occupants.
- Test Procedure Development.** Development of test procedures and test devices for a standardized

evaluation of vehicle aggressivity/compatibility.

- **International Harmonization Efforts.** Under this task, NHTSA will collaborate with international regulatory bodies and research organizations in vehicle compatibility research, e.g., the International Harmonized Research Activities committee. This committee was organized at the 15th ESV Conference and is led by representatives of the EC/EEVC. This will be a challenging effort due to differences in U.S. and international fleet composition (i.e., the U.S. has a large LTV fleet constituent which is not present in other continents/countries).

## CONCLUSIONS

This paper has examined the compatibility of LTVs and cars in vehicle-to-vehicle collisions. Using struck driver fatalities per crash involvement of the subject vehicle as an aggressivity metric, examination of U.S. crash statistics has clearly shown a striking incompatibility between cars and all categories of LTVs. LTVs now account for over one-third of light vehicles on U.S. highways, but collisions between cars and LTVs lead to over 50% of all fatalities in light vehicle-to-vehicle collisions. Furthermore, a disproportionate number of the fatalities in LTV-car crashes are incurred by the car occupants. The availability of newer safety countermeasures, e.g., air bags, appears to improve compatibility indirectly by improving the crashworthiness of later model vehicles. However, the fundamental incompatibility between cars and LTVs is observed even when the analysis is restricted to collisions between vehicles of model year 1990 or later -- indicating that the aggressivity of LTVs will persist even in future fleets. A comparison of LTVs and cars reveals that LTVs are more aggressive than cars for a number of reasons including their greater weight, stiffer structure, and higher ride height. This mismatch in design has serious consequences for crash safety as approximately one-half of all passenger vehicles sold in the U.S. are LTVs, and presents a growing source of incompatibility within the fleet.

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## IMPROVEMENT OF CRASH COMPATIBILITY BETWEEN CARS

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### ABSTRACT

This paper will provide an overview of the research work of the European Enhanced Vehicle-safety Committee (EEVC) in the field of crash compatibility between passenger cars. Since July 1997 the EC Commission is partly funding the research work of EEVC. The running period of this project will be two years. The progress of five working packages of this research project is presented: Literature review, Accident analysis, Structural survey of cars, Crash testing, and Mathematical modelling. According to the planned time schedule the progress of research work is different for the five working packages.

### INTRODUCTION

Road accidents are the greatest source of accidental death throughout the European Union. The installation and use of seat belts resulted in a major improvement in protection and paved the way for further improvements in car structures.

Recent research, by the European Enhanced Vehicle-safety Committee (EEVC), has resulted in the development of a test procedure for side impacts and a new frontal impact test procedure. During the development of these procedures, it has been recognised that there is an interaction between them. In protecting car occupants most activity has been associated with improving the occupants own car to aid his protection. In future, improvements should be possible from improving the front of the other car involved. The term „compatibility“ has been coined to describe this subject.

In February 1996 the EEVC Main Committee established the Working Group 15 to address to the problems of compatibility for the period of three years. The research work is done under the collaboration of the following partners: BASt, Chalmers University of Technology, Fiat, INRETS, INSIA/Universidad de Madrid, SWOV, TNO and TRL.

This project will provide for the start of a scientific approach to the question of compatibility. At the beginning, effort will be concentrated on the most important impact types: car to car frontal and side impacts. During this work, consideration will be given to the implications for pedestrian and other types of impact but they will not be directly addressed. Since July 1997 the research work is partly funded by the Commission of the European Community.

The work will cover three main activities:

Data from in depth accident studies will be used to identify the most important problems related to compatibility.

Typical accident configurations will be replicated by carrying out experimental car to car impacts. These crash tests should help to identify the major problems occurring when two cars impact.

Computer simulation modelling will be used to study the effects of changing the effective stiffness and mass of two cars impacting.

Vehicle incompatibilities can be observed in:

- structural incompatibility  
stiffness and  
geometry
- mass incompatibility.

Most vehicle safety experts agree that substantial reductions in casualties would be possible if the way cars interact in an accident were to be optimised. An estimate of the extent of possible benefits will be one of the outputs from the study.

## WORKING PACKAGE LITERATURE REVIEW

SWOV is responsible for this working package.

The objective of this literature review is to see how scientists define and tackle the problem of incompatibility between cars. The literature study is based on a vast range of documents, for which the papers and reports presented at the ESV-, IRCOBI-, STAPP- and SAE-conferences are important sources. The search includes documents from 1985 till now; older documents are considered only if members of EEVC-15 emphasise their relevancy and usefulness.

The results of the literature review on compatibility of cars regarding car to car crashes, are listed according to the following main topics:

- the statistical view
- the mechanical view
- the geometrical view.

In the statistical view subjects related to influence of vehicle mass, vehicle size and ranking are considered, based on (statistical) accident analysis. Newtonian mechanics, (in-depth) accident analysis, crash tests and computer simulation are studied in the mechanical view. The third topic, geometrical view, deals with specific subjects as distribution of stiffness and the influence of collision type, especially frontal collisions versus side impacts.

Clearly there is an overlap between these groups, since in statistical analysis both mechanical and geometrical aspects are used. Statistical analysis is treated separately from in-depth analysis because of the different methods, and quantity and quality of their outcome.

Preliminary findings are the following.

The statistical approach of vehicle compatibility is based on the quality of available accident data. Some authors conclude that the safety of cars is closely related to vehicle size, where others conclude that vehicle mass is the most important factor. Because of the relatively limited data available for statistical analysis, it is difficult to isolate vehicle mass and vehicle length from disturbing factors as driver age and driver attitude.

With Newtonian mechanics the problem of compatibility can only be described in a simple way. Particularly the

description of stiffness and vehicle shape are not well described in this view.

Data from in-depth studies can give additional information. More insight can be gained by crash tests and computer simulation. However, the problem of the latter two methods is that the relation between test data and real world accidents data (injury) is normally not available.

From a geometrical point of view compatibility is very complicated. There is a broad variance of vehicles on the road and there are numerous configurations of collisions. One individual car type may behave completely different in frontal and side collisions. Clearly the distribution of stiffness and the force levels by which cars absorb kinetic energy are important factors in the incompatibility problem.

From the interpretation of literature it is provisionally concluded in general that in car to car crashes, occupants in the smaller car are likely to be more severely injured than occupants in the bigger car. Hence, crash test(s) regarding compatibility should take the behaviour of the smallest cars of the vehicle population as reference.

## WORKING PACKAGE ACCIDENT ANALYSIS

INRETS is responsible for this working package.

EEVC WG 15 considers in depth studies carried out by different teams in Europe and official overall statistics in Germany and The Netherlands.

Up to now mass incompatibility has been identified and quantified in a large number of studies. One task of the compatibility project should be to come to a better description of the effects and better established figures concerning the quantification of injury severity resulting from this effect. The most successful method in this field seems to be the analysis of overall accident statistics for vehicle groups of similar structure. A comprehensive structural survey for passenger cars shall help to define those vehicle groups of comparable vehicle structure.

In some studies structural incompatibilities have been identified in car to car accidents between apparently incompatible vehicles, e.g. passenger cars vs. trucks or passenger cars vs. large MPV's, but such incompatibilities also exist between similar passenger cars. The main problem in this field is the identification of acceleration- or contact-related injuries. Both injury types can be caused by stiffness and/or geometry incompatibilities. One of the main topics of the compatibility project is the identification and quantification of incompatibilities between vehicles of similar mass and similar type. Both methods: in depth studies and overall statistics must be applied to solve this question.

Overall statistics can help to identify and quantify incompatibilities by using the vehicle structure data collected by INSIA (see next chapter). Several groups of different vehicle types but each with similar mass, similar structural stiffness or similar structural geometry should be defined. The accident severity of accidents between vehicles of two groups of the defined groups should be determined for each vehicle group. Different vehicle groups should show different injury severity levels. Driver gender and age as well as accident type and location should be considered to eliminate the influence of the driver.

## WORKING PACKAGE STRUCTURAL SURVEY OF CARS

INSIA, the vehicle engineering institute of the polytechnical University Madrid/Spain, is responsible for this working package. The survey done by INSIA is nearly completed. Minor improvements are under discussion.

**Introduction** - The parameters which have an influence in compatibility can be divided in three main groups:

- Mass of vehicles.
- Stiffness of structure.
- Geometrical compatibility.

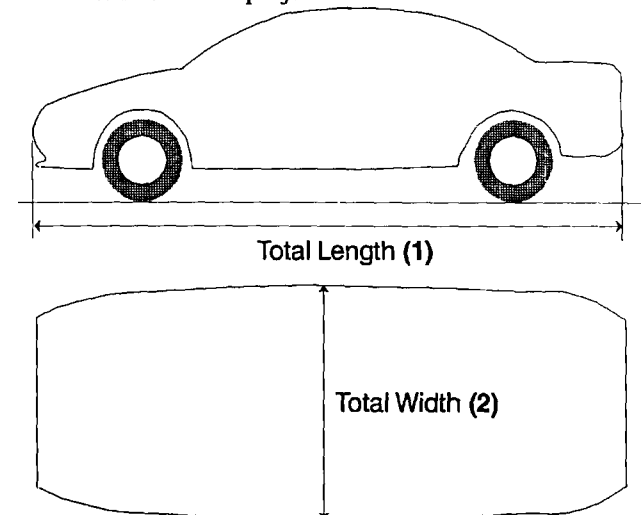
Conventional thinking tells us that when a smaller car collides with a larger one, the smaller car usually fares worse. In many studies was looked at a number of accidents, grouped the vehicles according to mass and then looked at the risk of injury to the occupants of the struck car and the risk to the occupants of the striking car. Perhaps unsurprisingly lighter cars seem to present less of a hazard to heavier cars.

So, the exterior risk associated with each model varied greatly within a given mass category. This conclusion illustrates that crash compatibility is not only influenced by mass but also by vehicle structure. The shape and crush stiffness of the sides and fronts of vehicles lead to intrusion problems.

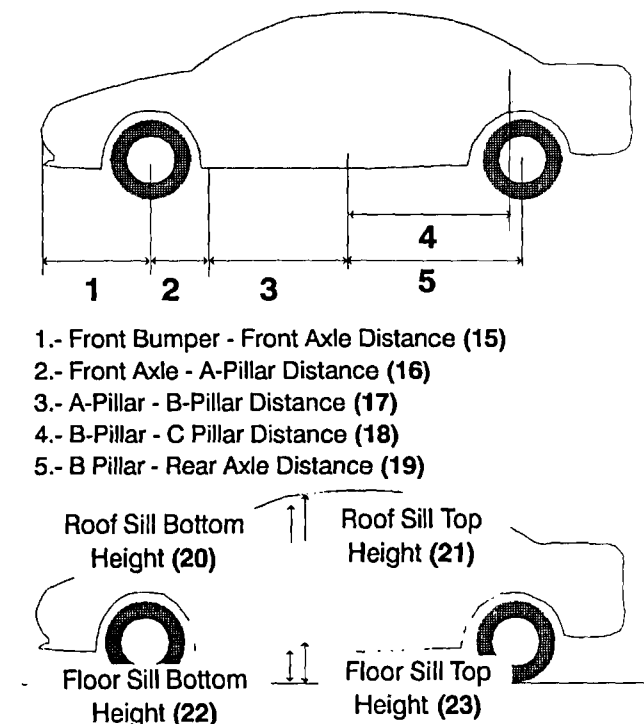
The structural survey examines the geometrical features of the resistant front and side elements, as inferred from vehicle measurements. Thus, this work is spread to a total number of **75 models** which have been selected from the main vehicle manufacturers in Spain. All of them have been sold for 1997.

**Methodology** - Detailed measurements have been taken of exterior and interior elements. Using the information available from the previous measurements in vehicles, the geometric characteristics of the main resistant

elements involved in the geometric compatibility between cars have been defined. These elements are presented in the following figures (*Figure 1, 2 and 3*), and have been divided in two main groups according to the vehicle zones studied in this project.



**Figure 1.- Definition of the main resistant elements. General dimensions.**



**Figure 2.- Definition of the main resistant elements. Side elements.**



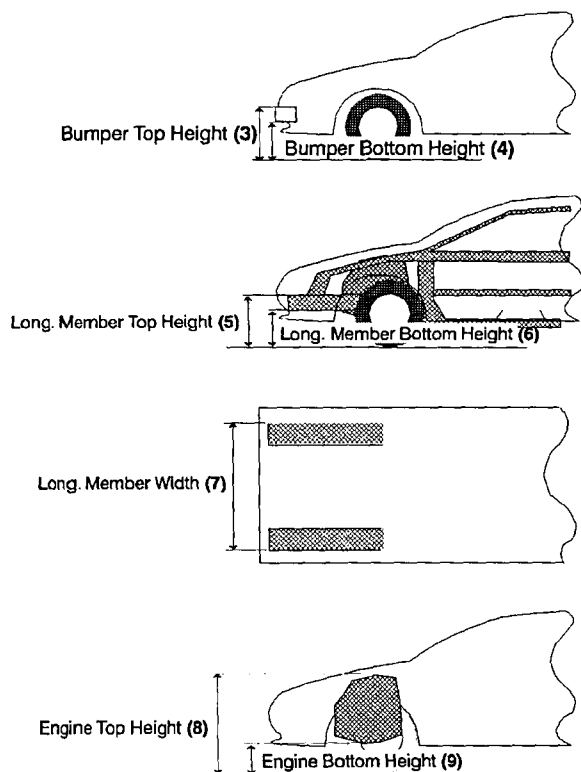


Figure 3.- Definition of the main resistant elements. Front elements.

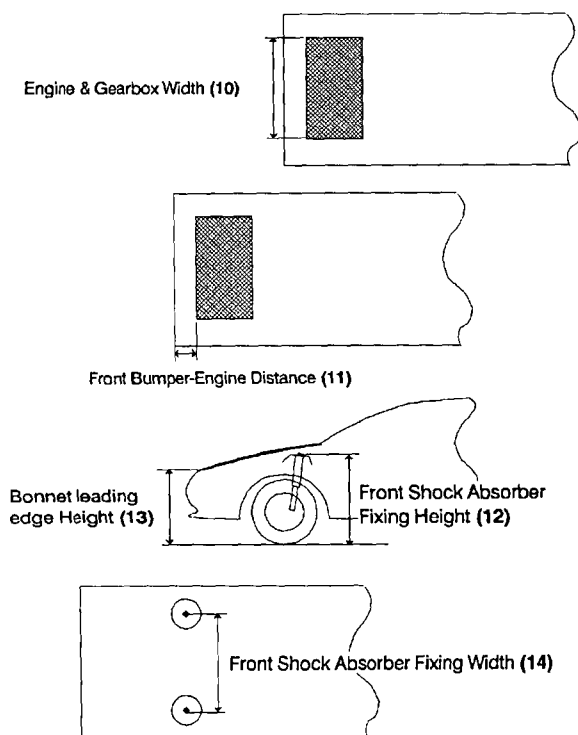


Figure 3.- Definition of the main resistant elements. Front elements (continued).

**Results - Vehicles involved** - As it has been presented in the previous text, this work is spread to a total number of **75 models** which have been selected from the main vehicle manufacturers in Spain. The distribution of these models according to the independent variables taken into account -*mass*, *length*- is shown in the following figures (Figure 4 and 5).

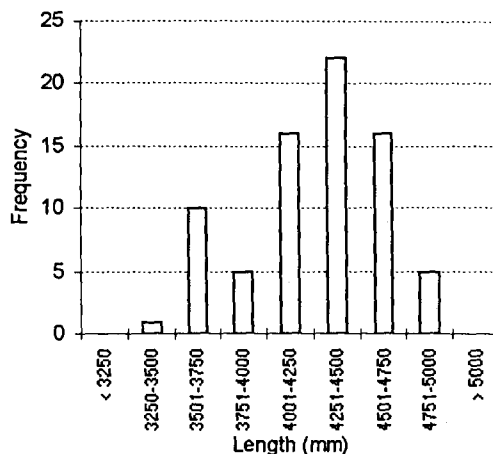


Figure 4.- Distribution of vehicle models by length.

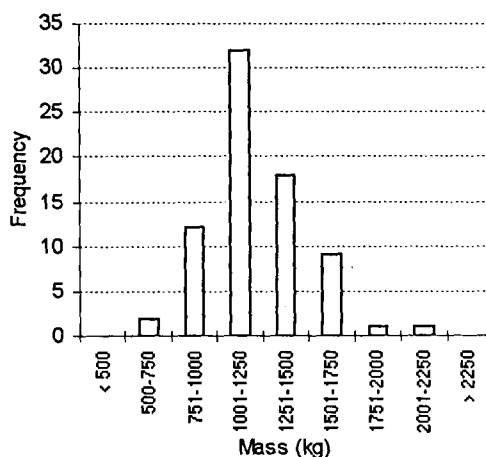


Figure 5.- Distribution of vehicle models by mass.

#### Results - Measurement Analysis:

**Linear Regression.** This phase consists of analysing the relations among the variables considered (resistant elements) and the independent variables: *mass* and *length*. This analysis has been developed by means of the following statistics:

- Linear parameters (least-squares coefficients): slope ( $B_1$ ) and intercept ( $B_0$ ).
- Standard error of the estimate ( $SEB_1$ ).

- **Testing hypothesis:** a frequently tested hypothesis is that there is no linear relationship between X and Y. The statistic used to test this hypothesis is  $t$ , which distribution, when the hypothesis of no linear is true, is Student's  $t$  distribution with  $N-2$  degrees of freedom. The significance level is 0.00005:

$$t = \frac{B_i}{SEB_i}$$

Taking into account these parameters, following linear relations have been found (Table 1).

**Table 1.**  
Linear relations among variables - (\*): transverse configuration engine; (\*\*): four/five-door models

INDEPENDENT VARIABLE: LENGTH											
		Value	SEBi	t	Sig. level			Value	SEBi	t	Sig. level
(10)(*)	B <sub>1</sub>	0.103	0.020	5.031	0.0000	(15)	B <sub>1</sub>	0.191	0.016	11.8	0.0000
	B <sub>0</sub>	441	86	5.115	0.0000		B <sub>0</sub>	31	69	0.45	0.6575
(11)	B <sub>1</sub>	0.141	0.027	5.124	0.0000	(16)	B <sub>1</sub>	0.12	0.026	4.56	0.0000
	B <sub>0</sub>	-109	117	-0.93	0.3557		B <sub>0</sub>	31	110	0.28	0.7810

INDEPENDENT VARIABLE: MASS											
		Value	SEBi	t	Sig. level			Value	SEBi	t	Sig. level
(8)	B <sub>1</sub>	0.113	0.023	4.84	0.00	(19)(**)	B <sub>1</sub>	0.319	0.064	5.01	0.00
	B <sub>0</sub>	675	29	23.17	0.00		B <sub>0</sub>	672	86	7.84	0.00
(15)	B <sub>1</sub>	0.206	0.030	6.81	0.00	(23)	B <sub>1</sub>	0.089	0.014	6.25	0.00
	B <sub>0</sub>	593	38	15.65	0.00		B <sub>0</sub>	235	18	13.19	0.00

### Results - Measurement Analysis:

**Mean values.** In this case, the dependent variables which do not show linear relation with length or mass are considered. Then, the mean values and the standard deviations are calculated. Afterwards, the different variables are compared, evaluating the relative position between them in case of collision (Tables 2 and 3).

**Table 2.**  
Relative distance between mean values of dependent variables. Horizontal dimensions.

Mean	(7)	(10')	(14)	(17)	(17')	(18)	(19)
value	1084	457	1083	1122	984	758	837
(7)	1084	0	-627	-1	38	-100	-326
(10')	457	627	0	626	665	527	301
(14)	1083	1	-626	0	39	-99	-325
(17)	1122	-38	-665	-39	0	-138	-364
(17')	984	100	-527	99	138	0	-226
(18)	758	326	-301	325	364	226	0
(19)	837	247	-380	246	285	147	-79

**Table 3.**  
Relative distance between mean values of dependent variables. Vertical dimensions.

Mean	(3)	(4)	(5)	(6)	(9)	(12)	(13)	(20)	(20')	(21)	(21')	(22)
values	543	382	522	411	192	836	723	1292	1555	1369	1667	222
(3)	543	0	-161	-21	-132	-351	293	180	749	1012	826	1124
(4)	382	161	0	140	29	-190	454	341	910	1173	987	1285
(5)	522	21	-140	0	-111	-330	314	201	770	1033	847	1145
(6)	411	132	-29	111	0	-219	425	312	881	1144	958	1256
(9)	192	351	190	330	219	0	644	531	1100	1363	1177	1475
(12)	836	-293	-454	-314	-425	-644	0	-113	456	719	533	831
(13)	723	-180	-341	-201	-312	-531	113	0	569	832	646	944
(20)	1292	-749	-910	-770	-881	-1100	-456	-569	0	263	77	375
(20')	1555	-1012	-1173	-1033	-1144	-1363	-719	-832	-263	0	-186	112
(21)	1369	-826	-987	-847	-958	-1177	-533	-646	-77	186	0	298
(21')	1667	-1124	-1285	-1145	-1256	-1475	-831	-944	-375	-112	-298	0
(22)	222	321	160	300	189	-30	614	501	1070	1333	1147	1445

(10'): longitudinal configuration engine;

(17): two/three-door models;

(17'): four/five-door models;

(20): without Off-Road, Commercial, MiniVan;

(20'): only Off-Road, Commercial, MiniVan

(21): without Off-Road, Commercial, MiniVan;

(21'): only Off-Road, Commercial, MiniVan

**Structural Survey Conclusion** - With the obtained results, the next conclusions are considered:

- There are only a few variables that show linear relation with length and mass.
- Using the mean values in case of lack of linear relation, the relative position between the different resistant elements considered can be analysed (collision).

## WORKING PACKAGE CRASH TESTING

TRL is responsible for this working package.

**Introduction** - TRL and BASt will carry out exploratory crash tests till mid 1998. In the second half of 1998 the generally agreed crash test programme will be commenced. Initial testing activities have focused on identifying the major factors which influence compatibility and determining the extent to which they might influence injury outcome. This work has been supplemented with exploratory testing with the aim of establishing possible, and practical, assessment methods.

### Car to Car Frontal Impact

**Interface Force** - Theoretical proposals are emerging as to possible ways of creating a compatible fleet. Many of these are in some way based around the control of the vehicles stiffness. In order to be able to assess the usefulness of these proposals, it is necessary to be able to quantify the characteristics of the vehicles global dynamic stiffness. One of the more useful measures of a vehicles stiffness is the level of interface force between impacting cars.

Interface force can be obtained through the use of a load cell wall or the measurement of the deceleration of the constituent parts of the vehicle. Both of these methods have been explored under this programme and for barrier tests have been shown to be in good agreement. In order to calculate the interface force from the car's deceleration, it is necessary to select and instrument discrete components and areas of structure. The selection is made based upon how it is believed these discrete areas of the vehicle will move and deform during the impact. It is assumed that the selected area will act as a lumped mass and the deceleration force for each lumped mass can be calculated from its associated deceleration. The summation of these forces gives the overall interface force (Figure 6.)

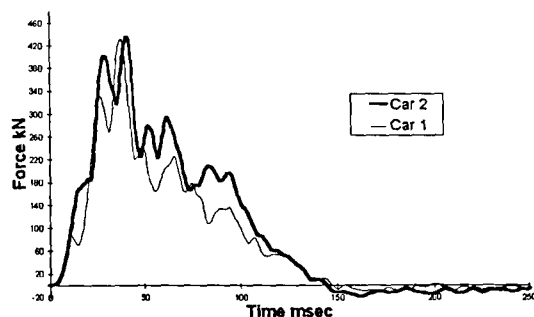


Figure 6.- Interface force calculated in car to car offset impact.

Now that this capability has been established, it will be used to gain an understanding of current interface force levels between impacting cars. In addition, it is envisaged that an assessment method will be created in order to validate the theoretical proposals developed to achieve a compatible fleet.

The interface work described above assumes that the fronts of vehicles interact well and that the 'average' stiffness which can be obtained from the interface force is sufficient. It is well known that the fronts of vehicles often have small areas of stiff structures within a larger area of weaker structure. For this reason it may well prove important to control the distribution of frontal stiffness, an area of research which is currently being undertaken to form part of the EC Compatibility Programme.

**Structural Interaction** - The control of the distribution of frontal structure is key to geometrical compatibility. Geometry, and how vehicles fronts interact, is one of the factors which influence vehicle compatibility along with vehicle mass and stiffness. However, the relative importance of each characteristic have yet to be established. Work has recently started to isolate and quantify the importance of each factor, starting with geometry.

In order to study the importance of structural compatibility, tests had to be conducted which had the sole variable of geometry. The first test carried out consisted of a medium size, car to car offset test. This was performed using identical vehicles, at the same test weight, but having undergone modifications to their ride heights. The vertical difference in height was 100mm, well within the fleet variations for this segment of car (5). The most noticeable difference in structural deformation of the two vehicles could be seen in the upper load path. In the lowered car, the struck side suspension turret had been displaced 480mm rearwards. By contrast, the suspension turret of the higher car moved rearwards by only 295mm.

In this test the vehicle's mass, stiffness and occupant compartment strength were matched. However, the 100mm vertical height difference was sufficient to noticeably change the vehicles structural response. When considering that the vertical height difference of the two vehicles was less than the height of the bumper beam, these results become significant. These preliminary observations have been obtained at the beginning of a testing programme, it will not be until further research has been conducted that any conclusions may be drawn. However, it is believed that until vehicle designs enable structures to interact better in car to car impacts, any compatibility improvements in mass ratios, or stiffness matching, are unlikely to be fully realised.

## WORKING PACKAGE MATHEMATICAL MODELLING

TNO is responsible for this working package. TRL and TNO are carrying out research work in this field. Their different approaches are described below.

**TRL-Approach - Introduction** - Initial research has focused on identifying the major factors which influence compatibility and determining the extent to which they might influence injury outcome. For frontal impact, the modelling work has studied how non-contact, deceleration related injuries might be minimised by optimising the deceleration pulse. For side impact, full car finite element models have been used for parametric studies to aid out understanding of the effects of the bullet vehicle mass, geometry and stiffness. This will help us to identify characteristics for more compatible car designs. Further details of the modelling approach and results are reported below.

**TRL-Approach Car to Car Frontal Impact** - There is virtually universal agreement amongst accident investigators that occupant compartment intrusion is a major cause of fatal and serious injuries to restrained occupants (1). In the future it is envisaged that car's occupant compartments will become stiffer so that there will be less intrusion in accidents. This is being driven by the introduction of Offset Barrier legislative and consumer impact tests. A probable outcome of this will be that there will be a reduction in the number of 'contact' related injuries and an increase in restraint system induced injuries. For this reason a study was initiated into the influence of the deceleration pulse on restraint related injuries, with the aim of modifying the pulse to minimise this type of injury. Having identified the most desirable shape we will, in later work, assess if it is possible to achieve such a pulse in real cars in a compatible fleet.

Computer simulation was selected as the most appropriate method by which to address this question. The MADYMO software package was used to simulate the deceleration of the occupant compartment (Figure 7).

Various simple shaped, analytical and experimental deceleration pulses were applied to the model in the fore aft direction. Chest injury criteria were monitored as the chest is directly loaded by the seat belt.

The results from this study, which are supported by previous work (2), indicate that:

1. Chest injury is minimised by maximising ridedown distance.
2. Chest injury is minimised by having a passenger compartment deceleration pulse profile that is constant in shape as opposed to triangular back loaded.

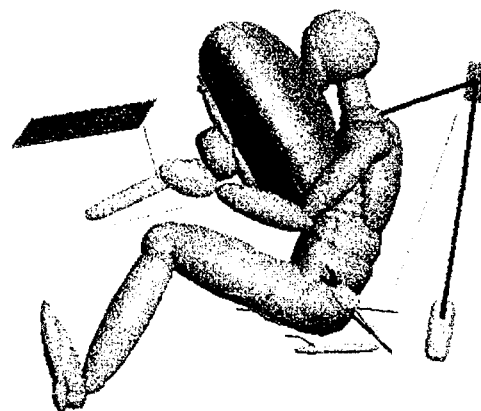


Figure 7.- Occupant compartment model; HYBRID III dummy held by a typical restraint system.

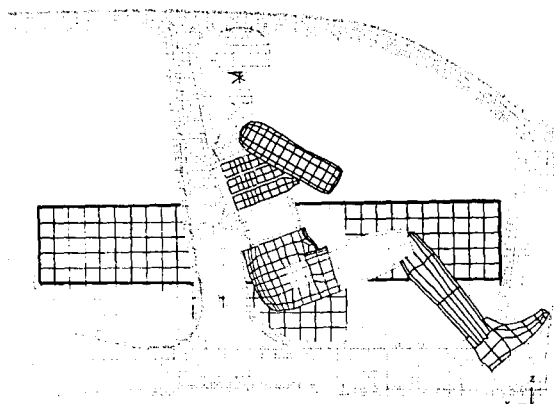
These findings have been demonstrated with deceleration pulses abstracted from experimental car crashes as well as analytical pulses.

It has also been shown that the deceleration pulse abstracted from a car to car 50 percent overlap impact, causes higher chest injury than the pulse from an ODB test. The reason for this is that the higher deceleration at the beginning of the car to car pulse means the occupant contacts the airbag with a higher velocity. This results in a high sternum to airbag load causing higher chest loading. A possible explanation for this is that the restraint system is 'tuned' to perform well in the ODB test. Manufacturers should be aware that the additional deceleration at the beginning of a car to car pulse compared to an ODB pulse can cause the occupant to contact the airbag with a greater velocity and hence induce higher chest compression. This would be difficult to compensate for in the adjustment of airbag trigger time as the beginning of the two pulses are very similar in shape.

**TRL-Approach Car to Car Side Impact** - The purpose of this study was to understand the effect of changing bullet vehicle parameters on the impacted cars structure and dummy response. In order to undertake such a parametric study, the European Mobile Deformable Barrier (MDB) was chosen as the bullet vehicle. It was assumed that changing the MDB characteristics would indicate trends similar to those from changing the characteristics of an impacting car.

The FE model of the small four door car, EUROSID and MDB, used for the study is shown (Figure 8). The model

was validated for an European side impact test and shown to give reasonable agreement.



**Figure 8.- Relative positions of MDB, EUROSID and car structure in European side impact test.**

A number of parameter sweeps were performed changing the following barrier characteristics:

1. Barrier centre impact point.
2. Barrier mass.
3. Barrier front face geometry.
4. Barrier stiffness.

Moving the barrier impact point down significantly reduced the EUROSID injury criteria as this gave better structural engagement with the sill. Raising the barrier had the opposite effect. Moving the barrier fore and aft did not have such a large effect on the injury criteria. This was an expected result as the amount of structural engagement did not change greatly.

Changing the barrier mass did not effect the injury criteria significantly as seen by other researchers (3). The reason for this is that most injury criteria peak before 40 ms whereas the momentum transfer is not complete until 80 - 100 ms. Also, the simple geometry changes made such as changing the barrier to have a planar front, did not significantly effect the injury criteria.

Changing the barrier stiffness had a significant effect. Stiffening the whole of the barrier increased all of the injury parameters, stiffening just the top of the barrier caused an even larger increase, but stiffening just the bottom of the barrier reduced chest injury.

In summary, the results of this study indicate that in order to improve compatibility for side impact, the bullet vehicle should be designed such that it engages the structure of the target vehicle more effectively through improved geometrical interaction. However, this should be achieved without compromising the intrusion profile, causing any unnecessary delay in the occupants accelera-

tion (4), or causing excessive roll in the target car. It is believed that excessive roll in the impacted vehicle may lead to head impact on the cant rail. Stiffening of the bullet cars upper load path without stiffening the lower path should be avoided as this will increase occupant injury. It should be noted that these conclusions have yet to be validated by experimental test.

**TNO Approach - Objective** - The objective of the workpackage Mathematical Modelling of Vehicles and Car Occupants is directly linked to the general objective of the research program, which is: to define optimal structural characteristics of a car fleet in order to get a minimum risk for getting seriously injured in the selected distribution of car to car collisions (front and side).

**TNO Approach - Contents** - The task Mathematical Modelling is subdivided in three subtasks:

- I. Vehicle modelling with Finite Element Methods: The objective of the numerical simulations with vehicle (FEM) models, is to understand in depth what principle mechanisms are involved during car to car crashes in terms of the interaction of the energy absorbing structures of the collision partners. In car to car crash tests only the post crash situation can be studied, as it is impossible to watch every single detail of the structure by means of high speed films or transducers. With these modelling techniques a tool is available to study different types of cars and many impact situations without additional costs for buying the cars and using test facilities. Even after finishing the project the models would be available to be used in subsequent studies on this subject. Additionally the models will be used to derive the characteristics of the structural parameters to be used in the lumped mass approach. TRL is the executing party for this part of the working package.
- II. Vehicle modelling with lumped mass models, occupant modelling and optimisation: The objective of using lumped mass models for the vehicle and the occupant is to run optimisations to define the optimum structural characteristics to get minimum risk for getting seriously injured for the selected distribution of accidents in the field. The reason for using lumped mass models is that current computer power to run optimisations with complete FEM models is not sufficient. TNO is the leading party for this part of the working package. The status is reported below.

- III. Verification of optimisation and findings from tests and accident investigations with FEM models.

Finally the new structural characteristics, have to be translated back to the structure by proposing design modifications that meet these new parameters. These modifications and modifications resulting from tests and accident investigations, can be build into the FEM models and verified for their actual performance in the car to car crashes.

#### **TNO Approach - Lumped mass Modelling detailed description and progress**

##### **Create very simple linear spring mass models**

###### **Objective:**

Study mass and global stiffness influence on compatibility. Increase the understanding on compatibility for frontal impacts only. For very first impressions on global stiffness and mass influences this approach is valid since from literature (6,7). It is known that indeed the global front stiffness of a car can be approximated roughly by a linear force deflection characteristic.

###### **Model specifications:**

A vehicle model consists of only one mass and one spring. The equations of motion can be solved analytically. The model can be used quite simple in a spreadsheet program and modifications of masses and stiffnesses can be entered easily.

###### **Status:**

The models give very quick the consequences of changing global vehicle parameters like stiffnesses, masses but also velocities, for the two vehicle models involved. The models can give an answer on the pre-assumptions that are made for what would mean, design a car for compatibility. The results show that it is very well possible to balance the global load levels of different mass vehicles for compatibility.

The final answer on this item has to follow from this EEVC study.

##### **TNO Approach - Create simple lumped mass models**

###### **Objective:**

Study mass and global stiffness influence on compatibility for front and side impacts.

###### **Model specifications:**

The front models should be capable to describe the global front stiffness, engine bay layout, contact engine to fire-wall, compartment stiffness and intrusion by engine, de-

livering realistic crash pulses for car to car frontal impacts.

###### **Status:**

General models have been created. Studies with model parameter variations have not been carried out yet. The model types have been proven to be valuable for the purpose they have to serve.

##### **Create complex 3D frame models**

###### **Objective:**

Include geometric incompatibility studies capability into the models. Study mass and global stiffness influence on compatibility. In the end, the models have to be used in optimisation runs where the safety level for the whole car population is optimised for the vehicle parameters, which are relevant for compatibility.

###### **Model specifications:**

The model should be capable to describe the interaction between vehicles. This means a detailed 3 D modelling of the front. "Hooking" should be described, however, it is not realistic to have the same level of detail as for FEM models to describe the contacts. The contacts and structural detail should be defined for a pre defined configuration and not for a general case.

The front-structure behaviour must be simulated correctly which means the major mechanisms of the structural elements must be simulated correctly. The occupants compartment intrusion must be simulated which means adequate surface description of the footwell, dashboard and steeringwheel behaviour must be simulated. As the models contain more detail the characteristics can be defined more in detail as well. For this purpose component calculations by means of FEM could be carried out or component tests can deliver the desired characteristics. For the side models the same models as in the simple models phase are applicable. In case FEM models give more information during the progress of the project, new details and information can be incorporated into the models. The interior of the car is part of the model including a HIII dummy. This dummy can be exchanged by different dummy sizes for studying the influence of measures and parameter changes to the dummy criteria.

The car models should be in three different car classes: light, medium heavy and one with clear geometric incompatibility characteristics. As it is very difficult to obtain data from the industry, car FE models which are available from NHTSA will be used to create the following car models.

- 1 Chrysler Neon
- 2 Ford Taurus
- 3 Geo Metro
- 4 Ford Explorer

This range of cars is estimated to be representative sample of the car population to study different phenomena, like mass dependency geometric influence and stiffness influence.

Both frontal and side models will be created.

#### Status:

The Chrysler Neon has been started as a common project between TNO and NHTSA. Figure 9 shows a representation of the undeformed geometry of the model of the vehicle only. The model has been validated for US NCAP frontal impact 35 mph including a HIII dummy. Figure 10 shows the vehicle and dummy model at 100 ms in a side view. For the vehicle results validation, see Figure 11 For the dummy results validation, see Figures 12,13,14. The HIC value in the test appeared to be 610 and in the simulation 547. For the current simulation still insufficient data for the airbag were available. Although already close, it is expected the end result will be even closer to the test.

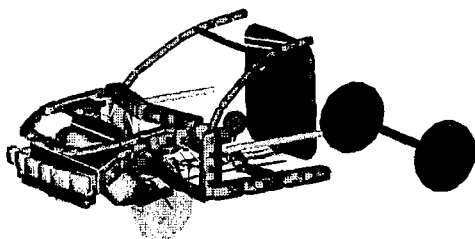


Figure 9.- Undeformed Geometry of 3D Frame model of Chrysler Neon

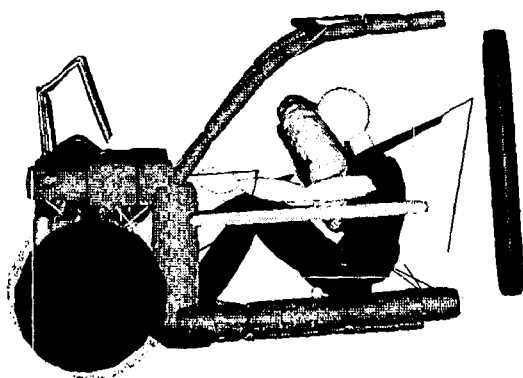


Figure 10.- Vehicle and HIII dummy model at 100 ms

The figures show an excellent model performance for this test configuration. Next step is to make the model use full for deformable offset and car to car (front and side) configurations.

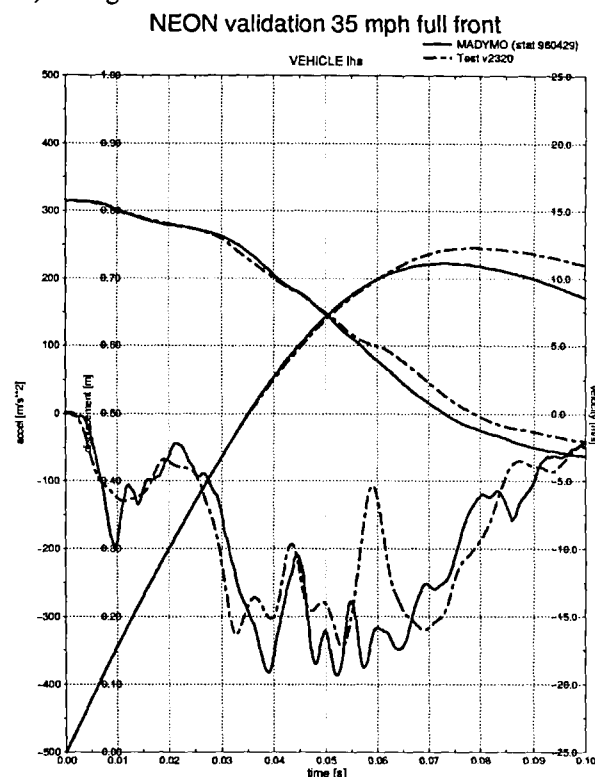


Figure 11.- Vehicle validation US NCAP

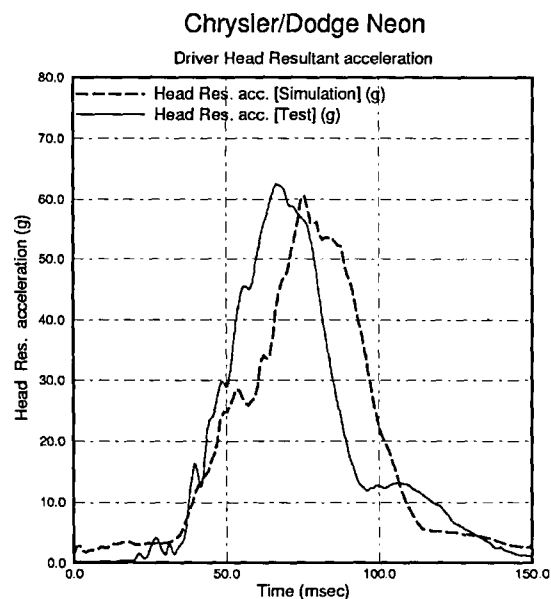


Figure 12.- Validation Resultant Head Acceleration

The work on the Ford Taurus has been started. The principle vehicle model is ready. Creation of the input characteristics for the deforming parts of the model still has to be carried out.

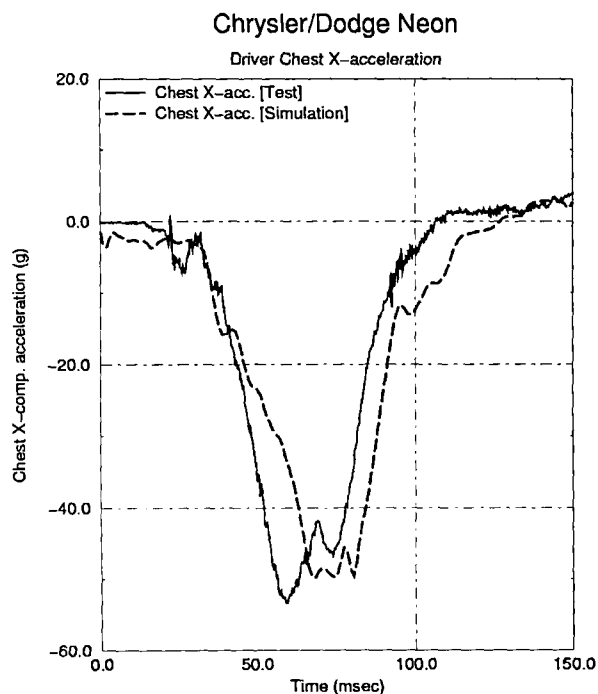


Figure 13.- Validation Resultant Chest Acceleration

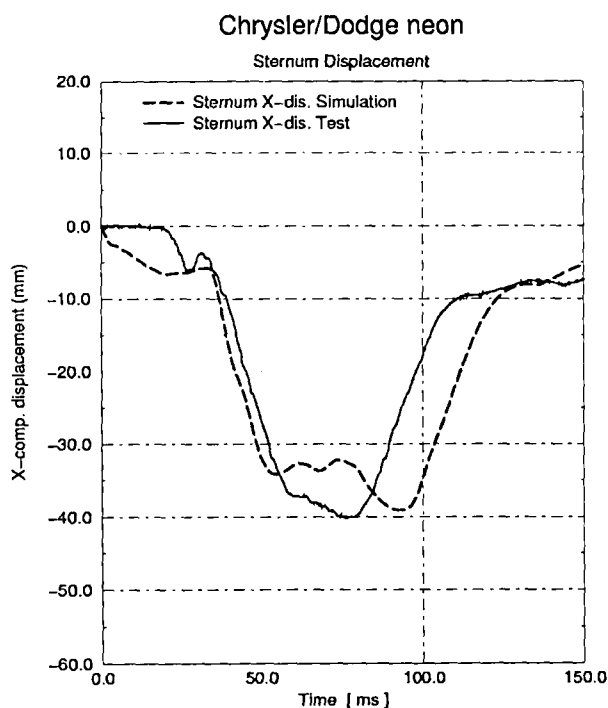


Figure 14.- Validation Sternum deflection

#### Side impact:

It is proposed to use frame models for the side structure for the side impact target cars. These models have proven validity in studying crash parameters (8). The model will be equipped with a Eurosid dummy model of the package MADYMO.

It is proposed to create models in four different type of weight classes conform the methodology in (9).

#### Status:

A 3D MADYMO frame model is presented in the MADYMO application manual (MADYMO 5.2). This model is used to study the influence of barrier mass and stiffness on the injury criteria of the Eurosid dummy. It was found that an increased stiffness of the barrier causes higher dummy loading in the thorax area, due to the dynamic behaviour of the side wall which is hit harder in case of a stiffer barrier. The higher mass has mainly effect on the final intrusion into the struck vehicle.

## CONCLUSION

First research work in the field of compatibility between cars has shown that analysing crash compatibility is an extremely complicated matter. It can be expected however that the multidisciplinary approach as established in this project will lead to substantial progress in understanding arising from vehicle incompatibility.

Besides studies in this research project the EEVC Working Group 15 (Compatibility) provides scientific input to the IHRA working group on the same topic. A close co-operation with a BRITE-EURAM project working also at the problem of vehicle compatibility is established. About this project a presentation is given at the same session of this ESV-Conference.

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## A SIMULATION STUDY ON THE MAJOR FACTORS IN COMPATIBILITY

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Paper Number 98-S3-O-03

### ABSTRACT

The evaluation method which simulates collisions between the subject vehicle and some other vehicle of a similar size has been developed up to now, by means of frontal impact to flat barrier or offset deformable barrier, etc. There are some reports describing that the injury level tends to become more severe for occupants of light vehicles than those of heavy vehicles, according to the accident data on vehicle-to-vehicle collisions. In this regard, the compatibility of heavy vehicles for the reduction of occupant injury level of lighter vehicles in such collisions is noted.

In this paper, the effect of factors has been studied by simulating the deformation of the struck vehicle. The influence on the impact performance of heavy vehicle into frontal impact barrier was also simulated.

### INTRODUCTION

The compatibility issue has been noted in recent years and related studies are being conducted at various research institutes. Although various proposals have been made so far, some of the proposals seem to contradict one another. Quantitative determinations of effects of individual factors have not become clear so far. Studies to estimate the effectiveness of each measure for the reduction of fatalities are also few.

It is likely that generally regarded major factors of compatibility are the vehicle weight, frontal stiffness and geometry. The effect of weight involves the following phenomena due to the laws of physics.

- A heavy vehicle requires a large amount of energy to be absorbed upon impact due to the large kinetic energy.
- In a collision between vehicles having different weights, the delta velocity ( $\Delta V$ ) of the lighter vehicle is higher than that of the heavier vehicle.

The injury level tends to become more severe for occupants of light vehicles than those of heavy vehicles, according to the accident data on vehicle-to-vehicle collisions. As the weight is closely related with other factors (vehicle size, stiffness, etc.), the quantitative determination of the effect of weight alone is not adequate.

The quantitative effect of stiffness or geometry has not become clear in accident analysis, since they have not been distinctively coded items in accident reports so far.

Some recent papers have noted that restraint systems in recent years (airbags, pretensioners, force limiters, etc.) may have decreased some of the influences of the laws of physics by improving occupant protection. According to that, the data used for the accident analysis in this study are restricted to belted drivers, and classified by vehicle weight.

Considering the above, the effect of frontal stiffness or vehicle weight has been studied by simulation. The effect on the subject vehicle performance in frontal impact into barrier has been also simulated. The FEM simulation models were prepared in hybrid form of beam/shell elements for the reduction of calculation time.

### INVESTIGATION ON ACCIDENT DATA

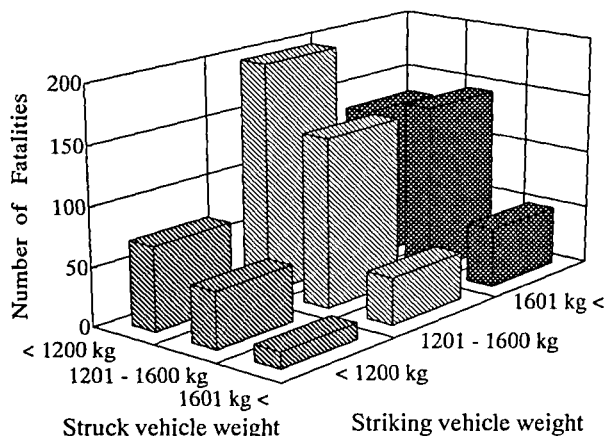
#### Distribution of Fatalities in Vehicle-to-Vehicle Frontal Collisions Classified by Vehicle Weight

The investigation was conducted based on '91-'95 FARS accident data. The accident configurations subjected to this investigation were as follows - vehicles of '91 to '95 model year with fatalities of belted drivers, vehicle to vehicle frontal collisions, excluding those of heavy duty trucks and motorcycles. The vehicles were classified into three classes in this study: light vehicles with a weight up to 1200 kg; mid-size vehicles with a weight in the range of 1201 to 1600 kg; and heavy vehicles with a weight of 1601 kg or more. The numbers of fatalities of struck vehicles are plotted according to this classification (Figure 1).

The number of fatalities is the greatest for the mid-size striking vehicles, followed by heavy vehicles. The view that the injury risk increases as the weight of the striking vehicle increases is not clear. Factors that affect the absolute numbers of fatalities include the differences in the number of vehicles registered for each weight class, miles driven per year of each vehicle category, the frontal stiffness of the striking vehicle, etc. in addition to the vehicle

weight.

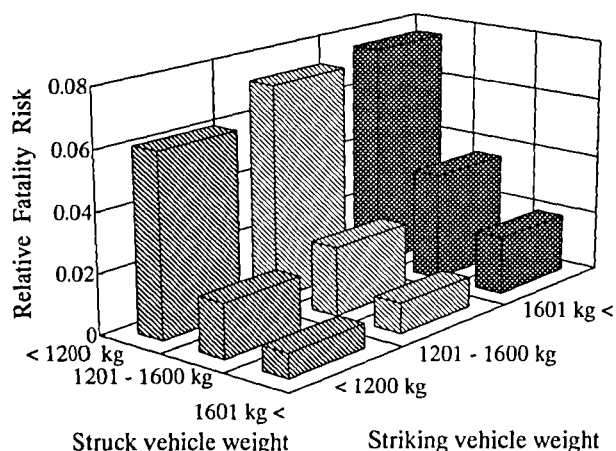
Accident data for cases with airbag deployments and driver fatalities were reviewed, but the sample size was so small that no conclusion could be made at this time.



**Figure 1. Fatalities distribution classified by vehicle weight, restricted to belted drivers in two vehicles frontal collisions.**

#### Estimation of Fatality Risk Distribution Classified by Vehicle Weight

To reduce the influence of the registration numbers of each weight class on the absolute number of fatalities, the relative fatality risk per one million registered vehicles was calculated for both striking vehicles and struck vehicles using the estimated cumulative data of the number of vehicles registered in '91 to '95. The distribution classified by vehicle weight is shown in Figure 2.

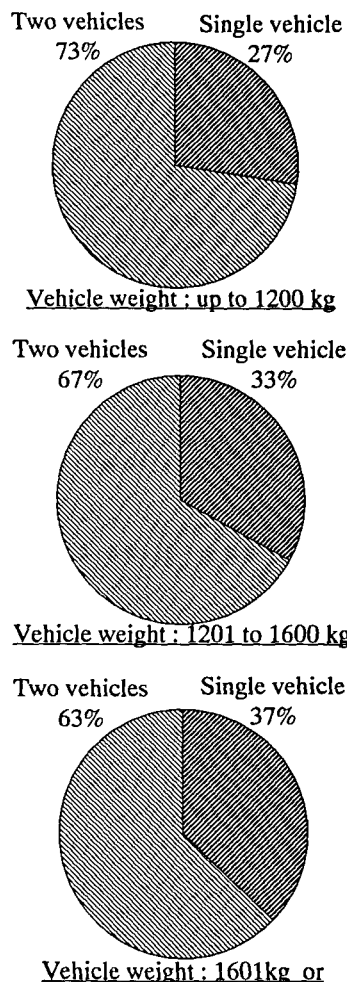


**Figure 2. Relative fatality risk distribution classified by vehicle weight, restricted to belted drivers in two vehicles frontal collisions.**

The effect of the striking vehicle's weight on the relative fatality risk indicates that the risk increases as the weight of the striking vehicle increases. According to the relative fatality risk distribution diagram, the risk is affected more significantly by the weight of the struck vehicle than the weight of the striking vehicle - possibly due to the restricted conditions (i.e. belted drivers, frontal collisions, etc.) of data investigated. As there are many other factors that affect the relative fatality risk including the frontal stiffness of the striking vehicle, miles driven per year, etc. in addition to the vehicle weight, efforts should also be made to determine their effects on the relative fatality risk.

#### Opposite Object for Each Weight Class in Frontal Collisions

The numbers of fatalities in single vehicle frontal collisions versus vehicle-to-vehicle frontal collisions have been investigated (Figure 3).



**Figure 3. Opposite object, restricted to belted fatal drivers in frontal collisions.**

Even in heavy vehicles, there are more fatalities in vehicle-to-vehicle frontal collisions than in single vehicle collisions. Further, the trend that the fatalities in single vehicle collisions increases as the weight increases is also observed. It is important to consider these facts.

## SIMULATIONS

### Preparation & Verification of Beam Element Models

To study the potential influence of factors other than vehicle weight, generalized simulation of impact were made using various finite element vehicle structures.

For the reduction of calculation time, beam element models excluding shell elements of front bumper and dash panel were prepared. The occupants were considered as nodal mass in the models. The number of beam elements for main body structures in each model was approximately 900 (Figure 4).

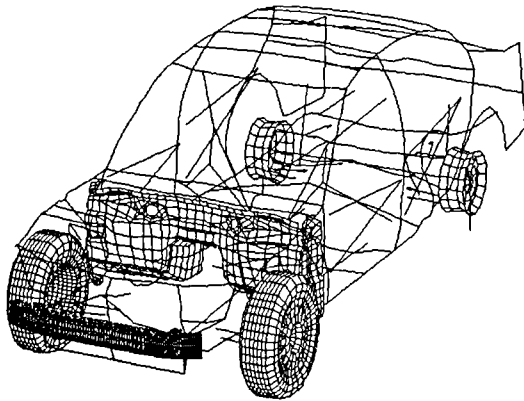


Figure 4. Beam elements model of body structures.

The models were verified by comparing the deformation - time characteristics with those of experimental data (Figure 5). The characteristics of each simulation model and the experimental data agreed fairly well.

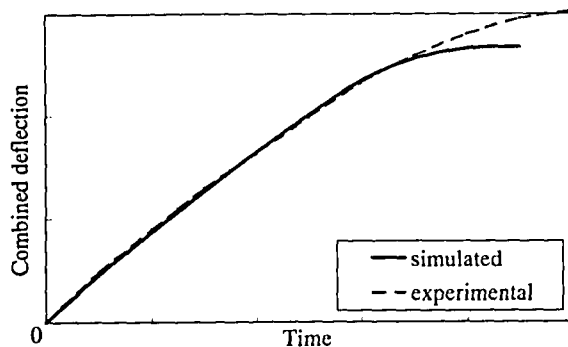


Figure 5. Comparison of simulated and experimental deflections in heavy car frontal impact to offset deformable barrier.

Two passenger car models - a light car (gross vehicle weight including the occupant mass: 1100 kg) and a heavy car (GVW including the occupant mass: 1700 kg) - were prepared. All simulations of car-to-car frontal impact were conducted at a closing speed of 100 km/h.

### Striking Car Models & Struck Car Deformation

The effect of differences of striking car characteristics on the deformation of the struck car in offset frontal impact was investigated using simulations. The effect of frontal overlap percentage was also studied. The overlap here refers to the percentage of overlap against the overall width of the struck car. The struck car was a light car and the simulation was conducted for both light and heavy striking cars. The delta V was 50 km/h for both striking and struck cars in the case where both cars were light, while it was 61 km/h for the struck light car and 39 km/h for the striking heavy car in the case of light car-to-heavy car impact due to the laws of physics.

The comparison of both cases where the overlap percentage are the same shows that the passenger compartment intrusion of the struck car struck by the heavy car is larger than struck by the light car (Figure 6). In cases where the overlap drops to 40 %, however, the light car deformation struck by a heavy car also drops to the same level as that of the case with the overlap exceeding 60 % struck by a light car. Hence as expected, the deformation of a struck vehicle is affected by the characteristics of the striking car models and also the impact overlap percentage.

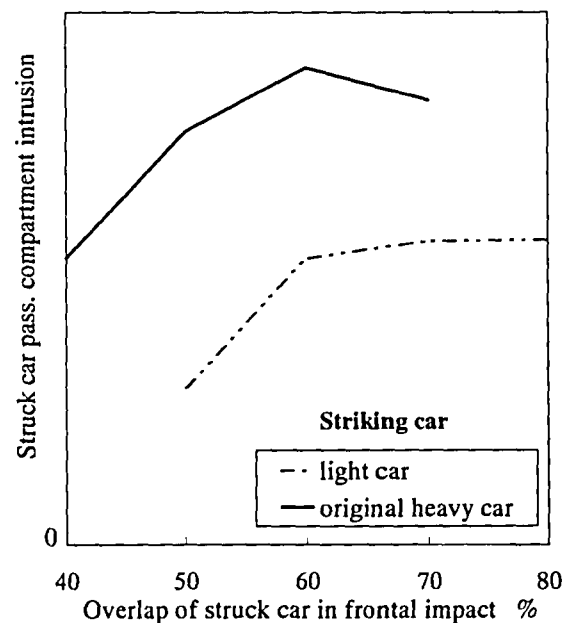


Figure 6. Effect of striking car model.

## Frontal Stiffness & Struck Car Deformation

The comparison of deformations between the cars shown in Figure 6 indicates that the struck car deformation is 1.7 times greater with the impact from the heavy car compared to the impact from the light car. For the investigation of the major factor of this phenomenon, the frontal stiffness or the mass of the striking heavy car was varied in simulations of impact configurations. Namely, the frontal stiffness of the heavy car was set at two levels - with 50 % increase and 50 % decrease, respectively, compared with the original level - while the weight was kept constant (Figure 7). The struck car deformation tends to be smaller as the striking car frontal stiffness is reduced (Figure 8), but the difference is smaller compared with the difference in frontal stiffness - i.e., 50 % difference in frontal stiffness versus 3 % or less difference in passenger compartment intrusion.

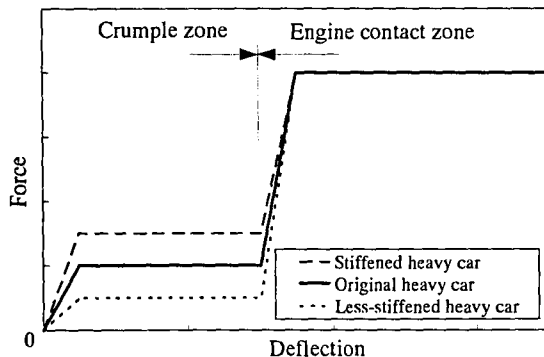


Figure 7. Comparison of heavy cars front stiffness, simplified diagram.

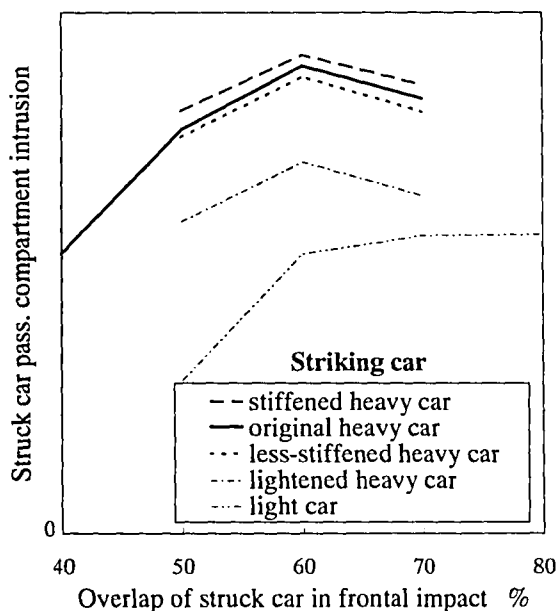


Figure 8. Effect of striking car's factors.

Figure 9 shows the car deceleration characteristics of the striking and struck cars. One of the factors of the above is due to this characteristics. The difference in frontal stiffness affects not only the struck car deformation but also the both cars deceleration dynamic characteristics. The deceleration in the initial stage of impact decreases with the drop of frontal stiffness due to the laws of physics, which, however, ultimately results in a greater overall deformation than those of the light car struck by an original stiffness heavy car. The combined deformation of both cars is represented by an area enveloped by the lines of deceleration characteristics of the striking and the struck cars. The reduction of the striking car's frontal stiffness shifts some of the combined deformation from the struck car to the striking car, but there is an overall increase in combined deformation due to the effect on the car deceleration dynamic characteristics. Consequently, it results in a smaller reduction of deformation of the struck car.

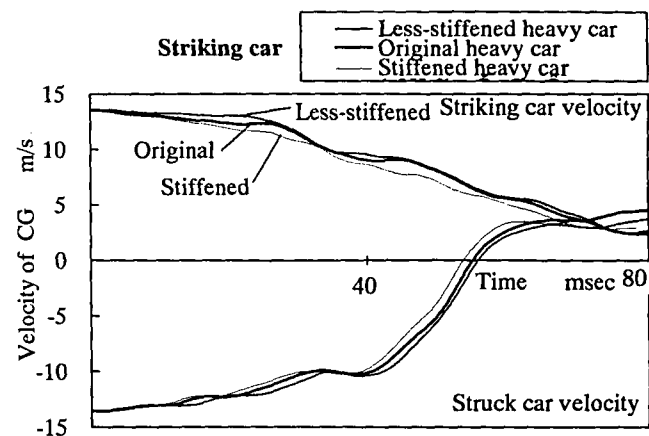


Figure 9. Vehicles deceleration characteristic.

## Car Weight & Struck Car Deformation

In other simulation, the stiffness was kept constant while the weight was reduced by 300 kg. The deformation of the struck car was reduced in accordance with the laws of physics (Figure 8).

## Effect of Stiffness on Subject Car Frontal Impact to Barrier

Simulations were conducted to observe the effect of frontal stiffness on the performance of the heavy striking car in the offset frontal deformable barrier impact. The intrusion tends to increase as the frontal stiffness drops (Figure 10). (19 % intrusion change caused by 50 % stiffness change)

Therefore, the reductions of frontal stiffness will have to be compensated for by increasing the vehicle's frontal crumple zone length. However, extending the car length will in-

crease the weight of the car which will affect the struck car's performance in car-to-car frontal collision.

By comparing the effect on the struck car's deformation in car-to-car frontal impact and the effect on the striking car's performance in offset frontal barrier impacts, the striking car's stiffness has little effect on the struck car deformation (19% the striking car's intrusion change in barrier impact versus 3% the struck car's intrusion change in car-to-car impact).

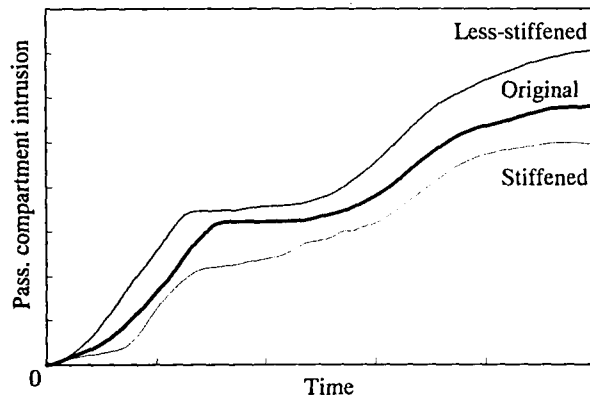


Figure 10. Effect of stiffness on deformation in offset frontal impact to deformable barrier.

## SUMMARY

In accident data investigation, the effect of vehicle weight on the occupant fatality risk is observed.

The quantitative effect of vehicle weight on occupant fatality risk cannot be determined, since there are some other factors which are not coded in existing accident data.

Computer simulations, however, can provide insights about the effect of weight and frontal stiffness characteristics of the striking car on the struck car's deformation.

- The simulations suggest that a 17% weight reduction of the striking car has a larger effect on compatibility than a 50% reduction of frontal stiffness in the striking car.
- Decreasing the stiffness of the striking car will reduce some deformation of the struck car. However, reducing the stiffness of the car will increase deformation of the car in frontal barrier impact testing.

The relationship between intrusion and occupant fatality risk is not yet clear. Efforts should be made in the future for the analysis of accident data with respect to air-bag systems and for the determination of the relationship between the vehicle intrusion and occupant fatality risk according to the results of accident data analysis.

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## COMPATIBILITY REQUIREMENTS FOR CARS IN FRONTAL AND SIDE IMPACT

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Paper Number 98-S3-O-04

### ABSTRACT

In support of the European Enhanced Vehicle-safety Committee (EEVC) research programme and through it, the International Harmonisation of Research Activities work on compatibility, TRL is investigating the compatibility of cars in frontal and side impact scenarios. Initial research has focused on identifying the major factors which influence compatibility and determining the extent to which they might influence injury outcome. Experimental crash test research is backed with Finite Element simulation modelling. For frontal impacts, full scale testing has been used to examine the influence of vehicle mass, stiffness, structural interaction and geometry. The modelling work has studied how non contact, deceleration related injuries might be minimised by optimising the deceleration pulse. For side impact, full car finite element models have been used for parametric studies to aid our understanding of the effects of the bullet vehicle mass, geometry and stiffness and to help predict more compatible designs. This has been backed by full scale crash testing, aimed at determining the ideal characteristics of interacting car front and side structures. All of this work is aimed at developing crash test requirements that are capable of assessing a car's compatibility.

### INTRODUCTION

It is now generally accepted by the international vehicle safety community that the 'compatibility' of vehicles needs to be addressed. The development of vehicles which simply 'self protect' will no longer be acceptable and growing emphasis must be placed upon the protection of all road users.

Each subsystem within the global fleet may currently possess its own unique 'incompatibilities'. A large number of U.S. publications are written about side impact and the problem associated with 'aggressive' sport utility vehicles and their mismatch with the midsize family saloon. This problem is exacerbated by a road system that gives rise to a large number of side impacts. In European

publications the emphasis is on frontal impact. However, it is well established that a compatible fleet can not be achieved through concentrating on a single impact scenario.

Research, guided by EEVC WG 15, which has been set up to study compatibility, will concentrate on both frontal and side car to car impacts. In addition it will also consider the requirements for car impacts with pedestrians, large vehicles and roadside obstacles. This should ensure that developments to improve car to car impacts do not reduce protection in these other types of impact.

In 1995 TRL commenced compatibility research stimulated by their findings from frontal and side impact testing. The programme is funded by the UK Department of Environment, Transport and the Regions and the European Commission. The work contributes to EEVC WG 15 and the International Harmonisation of Research Activities Compatibility Working Group.

The programme aims to identify how vehicle safety may be improved by developments to vehicle structures which are designed to interact better in an impact, and subsequently implement these changes in the vehicle fleet. This requires an understanding of the factors which influence compatibility and the development of new or modified legislative procedures to bring about greater compatibility. The project also aims to identify the potential benefits that could be obtained from improved compatibility.

This paper discusses those factors that are currently seen as having the greatest influence on compatibility and reports on the work carried out so far.

### CAR TO CAR IMPACTS

Current activities are focusing on car to car frontal impact and car to car side impact separately, in order to understand more clearly the controlling factors. It is envisaged that conflicting requirements will exist and that a compromise will have to be established. It is possible

that the current fleet differences between the U.S., Europe and other continents, will encourage researchers to reach differing compromises. It is for this reason that great importance must be placed upon international harmonisation in an attempt to reach a single, internationally appropriate, assessment procedure. One step towards compatibility may be the worldwide harmonisation of legislative and consumer testing.

## CAR TO CAR FRONTAL IMPACT

This section discusses those parameters which are currently seen as having the greatest influence on compatibility in frontal impact and presents the results from some of the work carried out so far.

### Collision Type

Collision type is the most important factor governing vehicle performance since it determines how the two car's structures will interact. For this reason, collision type will have a modifying influence on the effect of other parameters such as geometry and stiffness. For example, the effective global stiffness of a vehicle changes significantly from a full frontal impact to frontal offset impact, highlighting the importance of selecting the appropriate testing procedure (1). In this example, the differences in effective stiffness between the two collision types are attributed to the specific structures used for energy absorption and the modes by which they fail.

### Geometry

Car structures are designed to perform a multitude of functions as well as good crashworthiness. As a consequence, car fronts often have local areas of stiff structure within a much larger area of weaker structure. Due to this lack of stiffness uniformity it is usual in a car to car frontal impact, for the stiff parts of one vehicle to penetrate the weaker parts of the other. This may result in penetration fork effect or over-ride. Since in these situations the vehicle's energy absorbing structure is ineffectively used, higher occupant compartment intrusions are often observed. In one reported offset frontal test between a small and medium sized car, the poor structural interaction masked the effect of mass and stiffness and dominated the outcome (2). In this test the structure of the small car over-rode that of the medium sized car.

More recently this test has been repeated. The aim was to select a vehicle which would remove the previously reported geometrical incompatibilities and permit the assessment of mass and stiffness influence. The chosen substitute was a car that performed structurally well in the European Offset Deformable Barrier (ODB) test, whilst being of a similar mass to the car it replaced. In this repeat test the medium sized car, possessing better frontal structure tie-up, virtually eliminated over-riding (Figure 1.).



Figure 1. Medium size passenger car with well-connected front structures minimised over-ride by the small car.

Unfortunately, geometrical compatibility is not straight forward to assess. This was highlighted in an offset frontal car to car impact carried out between an off road vehicle and the medium size passenger car. It can be seen from the pre test photographs that there was a considerable difference in the vertical height of the significant structures of the two vehicles (Figure 2.).

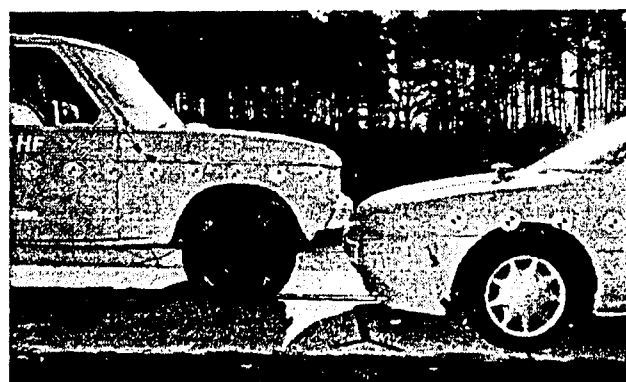
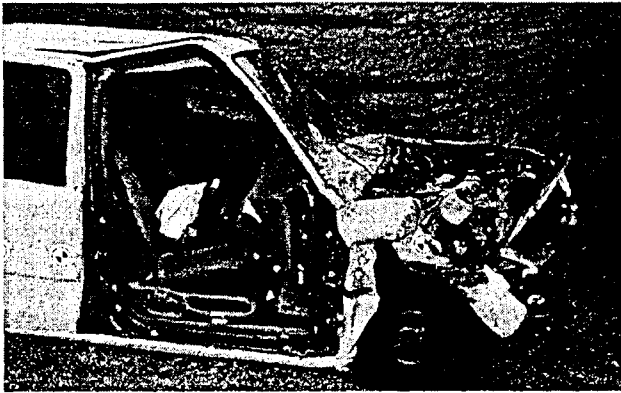


Figure 2. Geometrical differences between medium size passenger car and off road vehicle.

The results were contrary to expectations. The geometry of the two vehicles interacted well and there

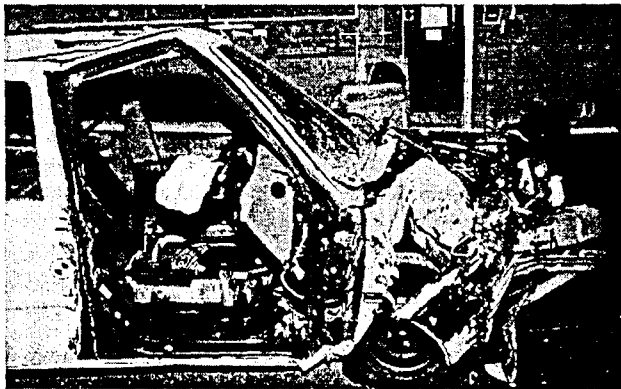


was no significant over-riding. In this particular test, the chassis rail of the off road vehicle engaged the suspension turret of the passenger car becoming retained by the engine mount attachment. A significant proportion of the loading was then transmitted through the engine and onto the firewall (Figure 3.).



**Figure 3.** Good geometrical interaction resulted in no significant over-riding by impacting 1900 kg off road vehicle, note intrusion at facia level.

The resulting deformation of the car's front structure and door aperture were not dissimilar to the results obtained from a car to car impact between two of the same medium size vehicles (Figure 4.)



**Figure 4.** Deformation of medium sized car after offset frontal impact with identical vehicle.

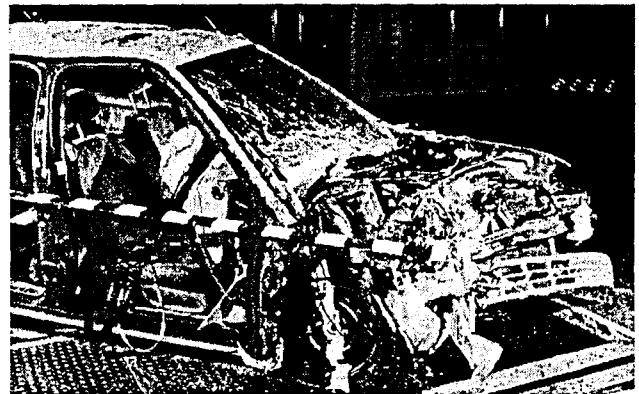
One significant difference, however, was the intrusion at facia level. In the car impacted by the off road vehicle, the additional loading directed onto the fire wall resulted in high occupant compartment intrusion, and as a consequence caused a higher chest deflection on the dummy. An important observation to note from this test is that the structures of two apparently incompatible vehicles

interacted in such a way as to virtually eliminate over-riding. Even though the good structural performance was not reflected in satisfactory dummy injury criteria (high chest deflection), this test goes part way to demonstrate that compatibility between dissimilar vehicles may be achievable.

In all of the tests commented on, it is a fair observation to make that geometry is not the only variable. Hence, in order to study the importance of structural compatibility, tests need to be conducted which have the sole variable of geometry.

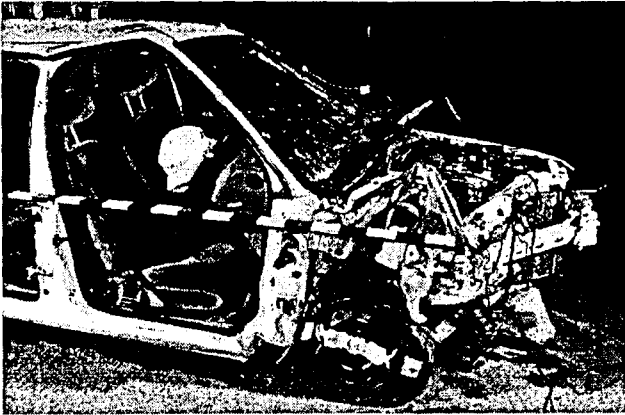
A medium size, car to car offset test was performed using identical vehicles, at the same test weight, but having undergone modifications to their ride heights. The vertical difference in height was 100mm, well within the fleet variations for this segment of car (3).

In the lowered car, a large proportion of the loading was carried by the upper load path (Figure 5.). This resulted in excessive intrusion at facia rail level and to a higher degree than that observed in the car impacted by the off road vehicle.



**Figure 5.** Lowered car, note 'A' pillar pushed down and high deformation at facia rail level.

In the lowered car the front profile was noticeably sloped back, and the 'A' pillar had been pushed downwards. The excessive deformation of the top load path meant the suspension turret had been displaced 480mm rearwards. By contrast, the suspension turret of the higher car moved rearwards by only 295mm. In this vehicle the 'A' pillar was pushed upwards increasing the deformation seen on the cant rail. More use was made of the lower load path and the frontal profile can be seen to be flatter (Figure 6.).



**Figure 6. Raised car - note 'A' pillar pushed up and little deformation at facia rail level.**

In this test the vehicle's mass, stiffness and occupant compartment strength were matched. However, the 100mm vertical height difference was sufficient to noticeably change the vehicles structural response. When considering that the vertical height difference of the two vehicles was less than the height of the bumper beam, these results become significant. Until vehicle designs enable structures to interact better in car to car impacts, any compatibility improvements in mass ratios, or stiffness matching, are unlikely to be fully realised. The authors suggest that in order to achieve a compatible fleet it will be necessary to firstly establish good geometrical compatibility.

### **Mass and Structural Stiffness**

The effect of mass and mass ratio on injury risk have been studied for many years and dominate the literature on compatibility. There is plenty of evidence that in car to car impacts the risk of injury in the heavier car is lower than that in the lighter car (4). However, whilst the authors do not dispute that mass has a significant effect on injury, it must be remembered that mass is a surrogate measure for other factors such as vehicle size, length of front structure and presence and quality of safety features. These factors could help to exaggerate the mass effect. It is also recognised that mass is a common parameter to record during accident investigation and as a consequence is available for data analysis.

In frontal accidents, occupants of lower mass vehicles often have higher injury risks due to both lower vehicle mass and stiffness (5,6). Ignoring crashworthiness, heavier cars are stiffer for other reasons, with structures

often being stronger to take the higher engine and suspension loads (2). There is, however, no certainty that the stiffness differential of small and large cars will continue to exist at the current ratio. There is clear evidence that the stiffness of smaller cars is increasing as a consequence of new crash test requirements.

There is virtually universal agreement amongst independent accident investigators that passenger compartment intrusion is a major cause of fatal and serious injuries to restrained car occupants. This view is also supported by many accident investigators employed by car manufacturers (5). In order to limit and manage occupant compartment intrusion in car to car frontal impacts, the crush zones of the cars involved must be capable of absorbing the full energy of the impact. A number of simple concepts have been proposed to control the global stiffness of the vehicle and hence improve compatibility.

The first proposal to note is that of a 'semi-rigid' passenger compartment (7). This suggestion involves designing the vehicle in such a manner that the occupant compartment is sufficiently stiff so that it can resist the deformation force put on it by any colliding car. This ensures that the impact energy is absorbed by the front structures of both cars.

Another suggestion has been made in which a limit is placed on the maximum crush force that must not be exceeded in a given impact (8). This concept has been extended with suggestions being made that both maximum and minimum force requirements are needed or that force corridors should be defined. These proposals are effectively equivalent to controlling the vehicle's stiffness.

Two fundamental questions need to be answered before pursuing either of these logical proposals:

1. What test could be performed to ensure that the occupant compartment could withstand the maximum crush force level?
2. What should the crush force level(s) be?

Currently there is no internationally recognised or legislative test which is capable of addressing the first question. It would be necessary to introduce an additional test to make such an assessment. Two possibilities may be a quasi-static crush, or a frontal test at an elevated speed. Neither of these solutions are however without drawbacks.

In order to be in a position to address the second of these questions it is important to have an understanding of current interface force levels between the impacting cars, and to be able to measure them in both barrier and car to car impacts. The proposals which have been commented on in this paper are theoretical and the first step must be to establish if such requirements could be achieved.

Interface force can be obtained through the use of a load cell wall or the measurement of the deceleration of the constituent parts of the vehicle. Both of these methods have been used at TRL and for barrier tests have been shown to be in good agreement (Figure 7.).

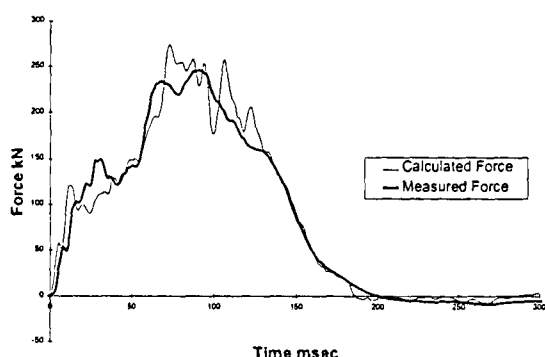


Figure 7. Interface force from frontal ODB test, note agreement between load cell wall data and interface force calculated from accelerometers.

In order to calculate the interface force from the car's deceleration, it is necessary to select and instrument discrete components and areas of structure. The selection is made based upon how it is believed these discrete areas of the vehicle will move and deform during the impact. It is assumed that the selected area will act as a lumped mass and the deceleration force for each lumped mass can be calculated from its associated deceleration. The summation of these forces gives the overall interface force (Figure 8.).

Differing views exist on how the total interface force could be limited or controlled. However, it should be possible to exercise control over vehicle local stiffness by limiting the interface force distribution. This type of control could be one way to improve geometrical compatibility.

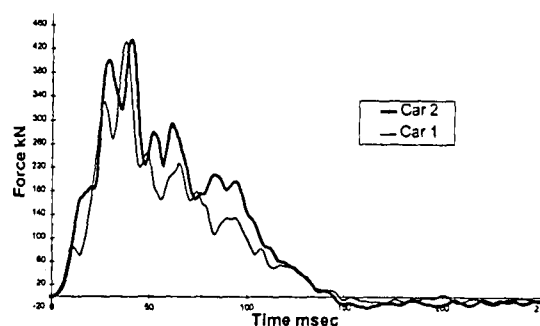


Figure 8. Interface force calculated in car to car offset impact.

With the semi rigid passenger compartment and the crush force limit theoretical concepts (7,8), it would be possible to achieve the requirements without controlling the shape of the deceleration pulse. It is the form of deceleration seen by the occupant compartment that drives the performance of the restraint system, and influences any restraint system induced injury. If we assume that our compatible vehicle has minimised intrusion due to the 'rigid' occupant cell, this type of injury will be dominant.

For this reason a study was initiated into the influence of the deceleration pulse on restraint system related injuries for frontal impact, with the aim of modifying the deceleration pulse to minimise this type of injury. Having identified the most desirable shape we will, in later work, assess if it is possible to achieve such a pulse in real cars.

Computer Simulation was selected as the most appropriate method by which to address this question. The MADYMO software package was used to simulate the deceleration of the occupant compartment. (Figure 9.).

Various simple shaped, analytical and experimental deceleration pulses were applied to the model in the fore aft direction. The Fourier Equivalent Wave (FEW) method (9) was used to generate a wide range of analytical deceleration pulses with predetermined ride down distances and times. This method sums three sine waves to produce a deceleration pulse :

$$a(t) = \sum_{N=1}^3 a_n \sin(n\omega t) \quad (1.)$$

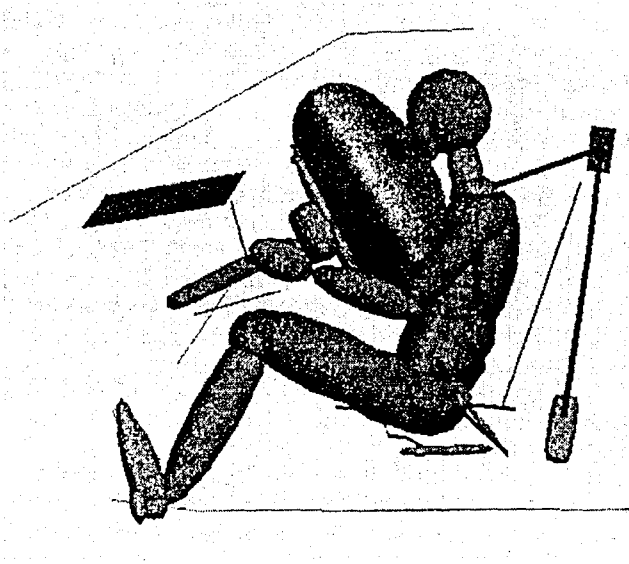


Figure 9. Occupant compartment model consisting of a HYBRID III dummy held by a typical restraint system.

Chest injury criteria were monitored as the chest is directly loaded by the seat belt. Peak chest compression was used as the measure of chest injury in the current study in preference to Viscous Criteria. Previous researchers who have studied the mechanism of impact induced soft tissue injury show that for a properly designed restraint system, the best indicator of injury is the peak chest compression (10).

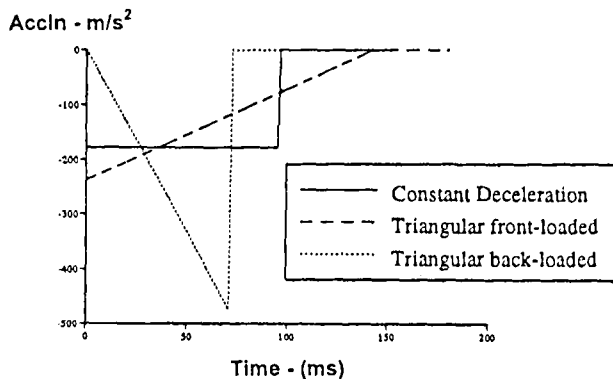


Figure 10. Comparison of simple shaped deceleration pulses for a ride down distance 0.8m.

Table 1.  
Chest Injury; Simple Deceleration Pulse Shapes, Ride down Distance 0.8m, Initial Velocity 61km/hr.

Shape	Ride Down Time (msec)	Chest Injury	
		Peak Comp (mm)	Peak Accln ( $\text{ms}^{-2}$ )
Constant	95	41 @62ms	359 @59ms
Triangular front loaded	142	44 @57ms	408 @55ms
Triangular back loaded	71	56 @78ms	618 @76ms

Investigations of the relationship between Hybrid III sternal deflection and thoracic injury severity on occupants have established that there is a 5 percent risk of injury greater or equal to AIS3 for a chest compression of 22mm. For a chest compression of 50mm the risk of injury greater or equal to AIS3 increases to 50 percent (11). Chest acceleration is also shown as a supplementary measure of injury.

The first parameter sweep applied three simple shaped deceleration pulses; constant, front loaded triangular and back loaded triangular, to the model to produce a ride down distance of 0.8 m (Figure 10.). This is a typical ride down for a 50 percent offset car to car impact. The results show that the constant pulse gives the lowest chest compression and the triangular back loaded the highest (Table 1.). An explanation for this emerges upon examination of the seat belt loads (Figure 11.).

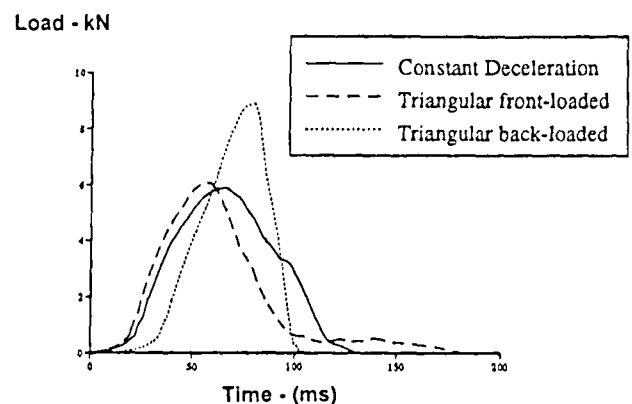


Figure 11. Comparison of seat belt loads for simple shaped deceleration pulses, ride down distance 0.8m.

The high deceleration at the beginning of the constant pulse, loads the occupant into the restraint system early. The constant deceleration, applied throughout the duration of the long ride down time, keeps the load applied over as long a time as possible to give a well rounded chest compression profile with a low peak (Figure 12.).

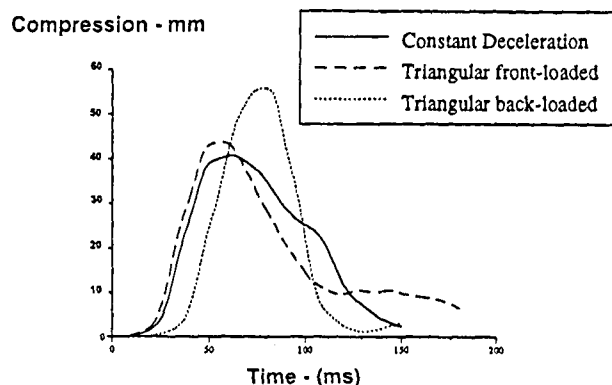


Figure 12. Comparison of chest compression for simple shaped deceleration pulses, ride down 0.8m.

In contrast, the low deceleration at the beginning of the back loaded triangular pulse loads the occupant into the restraint system late. As a consequence, a high restraining load is applied to the occupant for a short time, which results in a high peak chest compression. This also causes the peak chest compression to be at a much later time compared to the constant pulse.

A similar result is seen for a ride down distance of 1.2m which is a typical ride down for a car to ODB impact (Table 2.).

Table 2.  
Comparison of Chest Injury; Simple Deceleration  
Pulse Shapes, Ride down Distance 1.2m,  
Initial Velocity 61km/hr.

Shape	Ride down Time / msec	Chest Injury	
		Peak Comp (mm)	AccIn (ms <sup>-2</sup> )
constant	173	31 @67ms	226 @63ms
triangular front loaded	214	35 @63ms	266 @60ms
triangular back loaded	107	40 @104ms	404 @104ms

It is interesting to note that decreasing the ride down distance from 1.2 m to 0.8 m for a constant pulse has approximately the same effect on chest compression as keeping the ride down distance constant at 1.2 m and changing the shape of the pulse from a constant to a triangular back loaded pulse. These results are supported by previous work carried out at TRL (12).

Parameter sweeps were conducted using the analytically derived FEW deceleration pulses for various ride down distances. For this part of the study the airbag and steering wheel assembly was removed from the model. This eliminated the sensitivity of results to airbag trigger time. The double humped FEW pulse that gave the lowest chest compression for a ride down of 0.8m, is shown (Figure 13.), together with a graph of chest compression (Figure 14.).

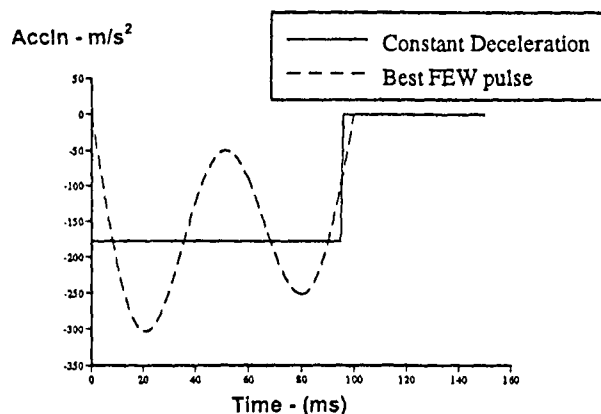


Figure 13. Comparison of doubled humped FEW and constant deceleration pulses.

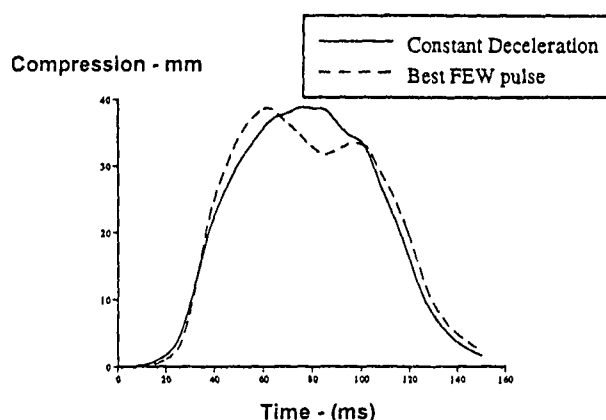


Figure 14. Comparison of chest compression for double humped FEW and constant deceleration pulses.

If these graphs are examined in detail it is seen that the double humped FEW pulse gives a low chest compression because of a similar behaviour to the constant pulse, i.e. the high deceleration at the beginning of the pulse loads the occupant into the restraint system early and the high deceleration at the end keeps the load applied for as long as possible.

Summarising, the results from this study indicate that :

1. Peak chest compression is minimised by maximising ride down distance.
2. Peak chest compression is minimised by having a passenger compartment deceleration pulse profile that is constant in shape as opposed to triangular back loaded.

The next part of the study abstracted the fore aft occupant compartment deceleration pulses from the following crash tests:

1. Car to car frontal impact with 50 percent overlap at an initial velocity of 56 km/hr.
2. European ODB test with 40 percent overlap but at an initial velocity of 61 km/hr.
3. Light car impacted by heavy car (mass ratio 1.4) with 50 percent overlap at an initial velocity of 56 km/hr.

4. Heavy car impacted by light car (mass ratio 1.4) with 50 percent overlap at an initial velocity of 56 km/hr.
5. Car to rigid barrier test with 100 percent overlap at an initial velocity of 56 km/hr.

It should be noted that in all of these crash tests the same model of mid sized family car was used. These pulses were applied to the model, in order to determine occupant response without any passenger compartment intrusion. Two restraint systems were modelled; the first was a seatbelt only system, and the second a seatbelt and airbag system. The results of applying these pulses to the model for both restraint systems are shown below (Table 3.).

Firstly, we will discuss the differences between the model response for the car to car 50 percent overlap and the ODB deceleration pulses. A comparison of the deceleration pulses is shown (Figure 15.).

For the seatbelt only system, it is seen that the chest compression is higher for the ODB deceleration pulse (Figure 16.). This shows that the advantage of having a longer ride down distance is out-weighted by the increase in velocity and the change in the shape of the pulse, i.e. to a more triangular back loaded form.

**Table 3.**  
**Chest injury model results obtained by applying deceleration pulses abstracted from crash tests.**

Deceleration Pulse Description	$\Delta V$	Ride-down Distance	Seatbelt restraint system		Seatbelt and airbag restraint system	
	(km/hr)		Chest Comp (mm)	Chest Accln ( $ms^{-2}$ )	Chest Comp (mm)	Chest Accln ( $ms^{-2}$ )
1. Car to car 50% overlap	56	1.0	37	305	38	327
2. Offset Deformable Barrier 40% overlap	61	1.2	41	335	35	341
3. <u>Light</u> car impacted by heavy car 50% overlap	65	0.8	42	370	44	422
4. <u>Heavy</u> car impacted by light car 50% overlap	47	1.2	33	252	33	257
5. Full frontal rigid barrier 100% overlap	56	0.7	43	365	43	405

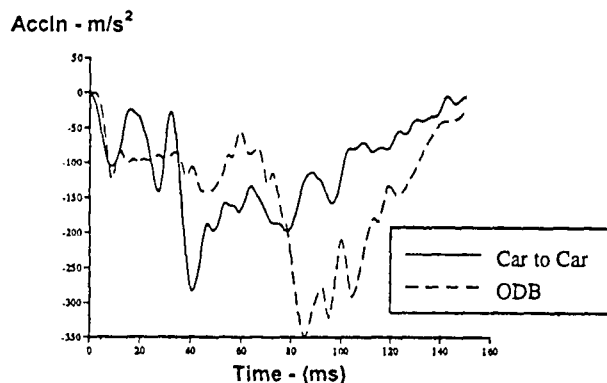


Figure 15. Comparison of deceleration pulse shape for ODB and 50 percent car to car.

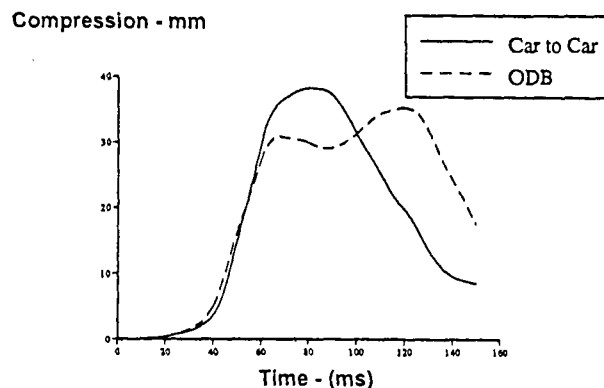


Figure 17. Comparison of chest compression for car to car and ODB impacts with seatbelt and airbag restraint system.

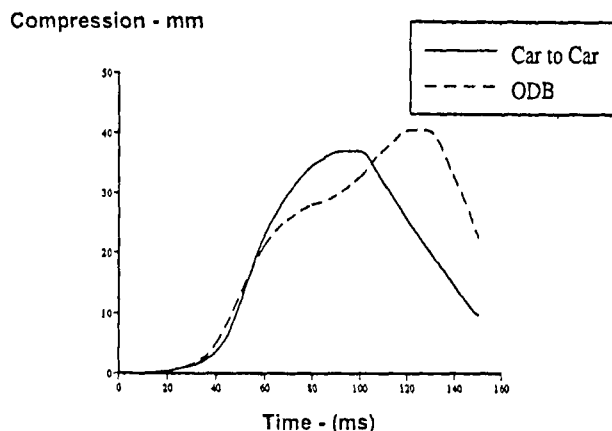


Figure 16. Comparison of chest compression for car to car and ODB impact with seatbelt restraint system.

For the seatbelt and airbag system it is seen that the chest compression is higher for the car to car deceleration pulse (Figure 17.). The reason for this is that the higher deceleration at the beginning of the car to car pulse causes the occupant to contact the airbag with a higher velocity giving a high sternum to airbag load (Figure 18.), so causing higher chest compression. One possible explanation for this is that the restraint system is 'tuned' to perform well in the ODB test. Manufacturers should be aware that the additional deceleration at the beginning of a car to car pulse compared to an ODB pulse can cause the occupant to contact the airbag with a greater velocity hence causing higher chest loads.

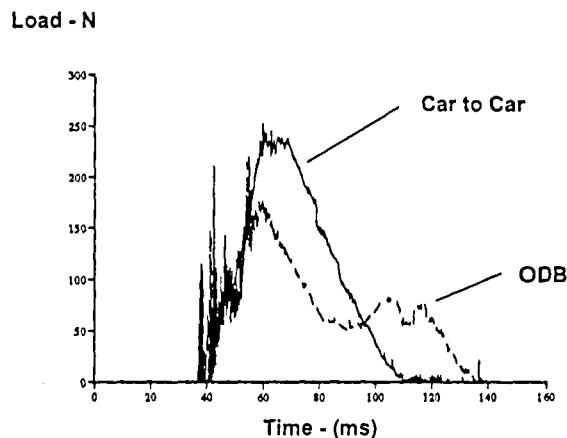


Figure 18. Comparison of sternum load from airbag for car to car and ODB impacts.

This would be difficult to allow for by adjusting the airbag trigger time, as the beginning of the pulses are very similar.

Secondly, we will compare the differences in the model response by applying the deceleration pulse from the car to car test with the pulses from the cars in the light to heavy car test (Figure 19.). The deceleration pulse from the light car has a more triangular back loaded shape, whilst the pulse from the heavy car has a more constant form. In addition the ride down is less and the change in velocity greater for the lighter car (Table 3.). It should be noted again that these cars are the same model and hence have the same stiffness

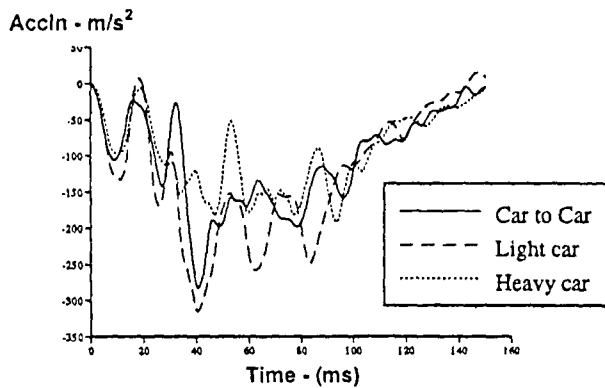


Figure 19. Comparison of deceleration pulse shapes for car to car and light to heavy car impacts.

In summary, in a car to car impact with cars of a similar stiffness, the occupant in the heavier car is subjected to a deceleration pulse that causes least injury in terms of ride down distance and shape. The converse is true for the occupant of the lighter car (Figure 20.).

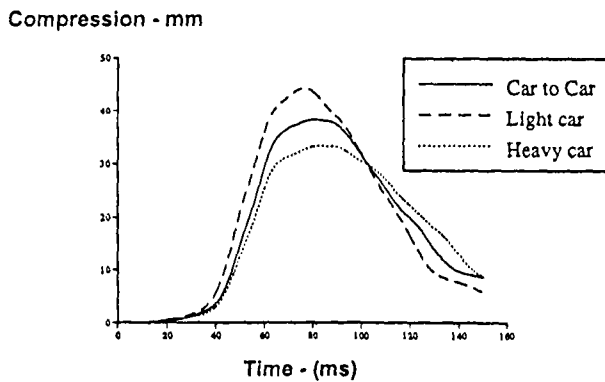


Figure 20. Comparison of chest compression for car to car and light to heavy car impacts.

Finally, we will consider the results obtained by applying the deceleration pulse from the full frontal rigid barrier test to the model (Figure 21.). The ride down distance for this deceleration pulse is the lowest (0.7 m) and hence considering this factor alone would be expected to give a high peak chest compression. In fact, the chest compression is not particularly high (Figure 22.). The low chest compression is a consequence of the near constant deceleration profile. This profile is most likely the result of manufacturers designing cars to meet and perform well in full frontal rigid wall legislative and consumer tests.

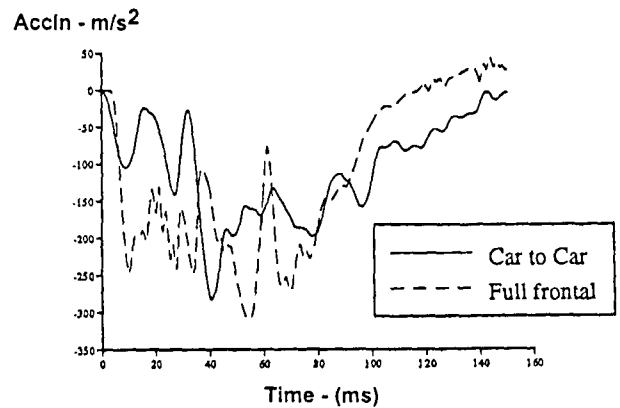


Figure 21. Comparison of deceleration pulse shapes for car to car and full frontal rigid wall impacts.

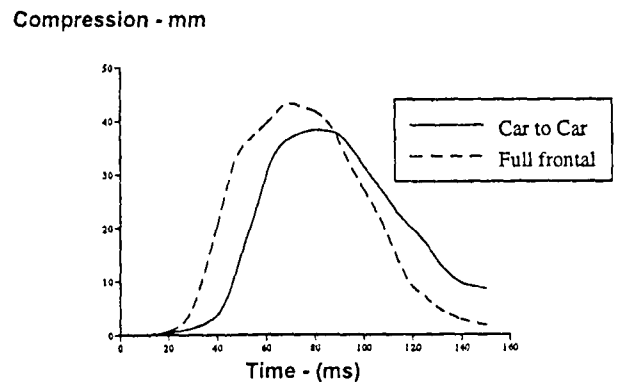


Figure 22. Comparison of chest compression for car to car and full frontal rigid wall impacts.

This study has indicated that in order to minimise chest injury the passenger compartment deceleration pulse should have a constant profile as opposed to a triangular back loaded profile, and ride down distance should be maximised. This has also been demonstrated with pulses from experimental car crashes.

The authors recognise that this study has used some theoretical deceleration pulses which may be impractical. However, a comprehensive range of pulses was investigated in order to quantify possible benefits before the study was restricted with practical considerations. In the future this study will be extended to help quantify the potential benefits of controlling the stiffness and



deceleration pulse shape of vehicles in a 'compatible fleet'.

## CAR TO CAR SIDE IMPACT

For side impact, parametric studies have been carried out using full car finite element models. The aim of this work was to aid our understanding of the effects of the bullet vehicle's mass, geometry and stiffness on the impacted car's structure and occupants response. This will help us to identify car structure characteristics which will improve compatibility. The modelling has been supported by full scale crash testing.

### Finite Element Modelling

The purpose of this study was to understand the effect of changing bullet vehicle parameters on the impacted car's structure and dummy response. In order to undertake such a parametric study, the European Mobile Deformable Barrier (MDB) was chosen as the bullet vehicle. It was assumed that changing the MDB characteristics would indicate trends similar to those from changing the characteristics of an impacting car.

The FE model of the small four door car, EUROSID and MDB, used for the study is shown below (Figure 23.).

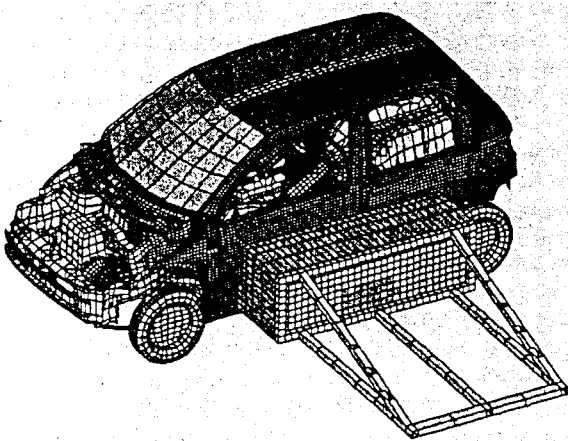


Figure 23. Small car FE model.

The model was validated for an European side impact test and shown to give reasonable agreement. The resulting vertical intrusion profile from this test is an indicator of a good structural response expected from a well designed modern car (13). In order to understand the results from the study it is important to understand the structural

interaction between the barrier, the car and EUROSID. For this purpose the position of the barrier relative to EUROSID and the main side structure of the car is shown. It is seen that the bottom of the barrier just interacts with the sill and that the bottom stiffer half of the barrier is just in line with lower part of the EUROSID pelvis. There is limited contact with the 'A' and 'C' pillars (Figure 24.).

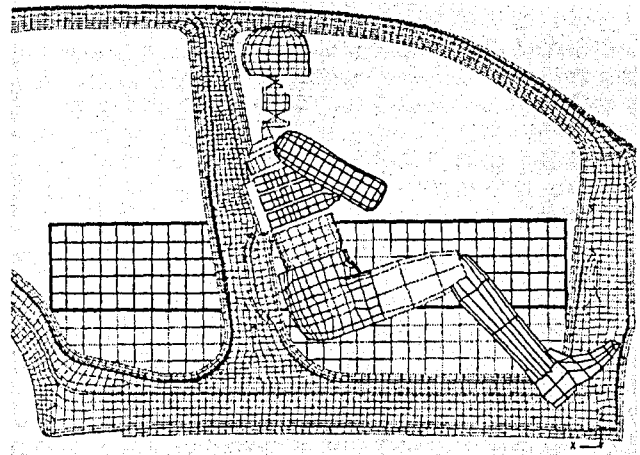


Figure 24. Relative positions of MDB, EUROSID and car structure in European side impact test.

A number of parameter sweeps were performed changing the following barrier characteristics:

1. Barrier centre impact point.
2. Barrier mass.
3. Barrier front face geometry.
4. Barrier stiffness.

Firstly, we will consider the effect of changing the point of impact of the barrier centre. For a standard European side impact test this is 550 mm above ground level in line with the R-point. This gives a barrier ground clearance of 300 mm (Table 4).

The form of these results can be explained in terms of the load paths into the car and its subsequent structural response. The two paths that we are considering are the load path through the door into the occupant and through the car's structure to its distributed mass. Ideally, we would like to reduce the load through the door into the occupant by putting more load directly into the car's structure. Whilst achieving this, the vertical intrusion profile should be maintained and any unnecessary delay in the occupant's acceleration should be avoided.

**Table 4.**  
**Injury Parameters with Varying Barrier Impact Point**  
**- European Side Impact Test as Reference.**

Barrier centre impact point	Reference (Euro)	Lowered 100 mm	Raised 100 mm	Fore 200 mm	Aft 200 mm
<b>Chest Compression (mm)</b>					
Top rib	35	24	47	31	37
Middle rib	35	21	49	32	37
Bottom rib	32	20	44	30	32
<b>Viscous Criteria (m/s)</b>					
Top rib	0.58	0.22	0.74	0.50	0.59
Middle rib	0.63	0.26	0.93	0.55	0.63
Bottom rib	0.53	0.20	1.0	0.48	0.53
<b>Abdomen Total</b>					
Force (kN)	1.9	1.6	2.2	2.1	2.0
<b>Pubic Symphysis</b>					
Force (kN)	3.7	3.2	4.1	3.6	4.4

Lowering the barrier achieves this by giving better structural engagement with the sill. Raising the barrier has the opposite effect and changes the intrusion profile to put additional load on the chest. Moving the barrier fore and aft does not have such a large effect on the injury criteria as moving the barrier up and down. This is an expected result as the amount of structural engagement does not change greatly. Any additional interaction with the 'A' and 'C' pillars is with the weak edges of the barrier. These parameter sweeps indicate that more structural engagement with the sill can result in lower injury. However, a test conducted at TRL in which good structural engagement with the sill was achieved caused significant amounts of roll on the target car (Figure 25.). This may not be desirable as excessive roll may lead to head impacts on the cant rail.



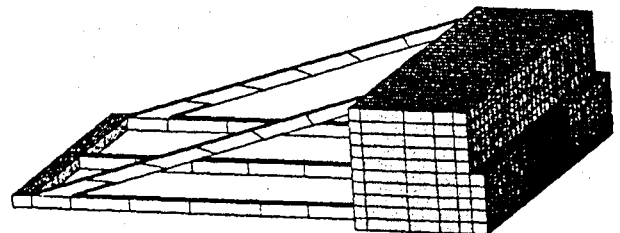
**Figure 25.** Good Structural Engagement Inducing Significant Role in Target Vehicle.

Secondly, we will consider the effect of changing the barrier mass (Table 5.). The mass of the car modelled was about 800 kg. The effects on the dummy injury criteria are not as great as one might expect, considering the large changes in mass. The reason for this is that the most of the injury criteria peak before 40 ms whereas the momentum transfer is not complete until 80 - 100 msec. However, this effect is larger than that observed in a previous test conducted at TRL where no significant change in injury criteria was seen when changing the barrier mass from 950 kg to 1350 kg, with a car mass of 1080 kg (14). A possible explanation for this is that the stiffness of cars in side impact has increased, hence the momentum transfer is earlier, so mass can have a greater effect on injury criteria.

**Table 5.**  
**Injury Parameters with Varying Barrier Mass -**  
**European Side Impact Barrier as Reference.**

Barrier mass	950 kg (Euro)	500 kg	1500 kg
<b>Chest Compression (mm)</b>			
Top rib	35	32	37
Middle rib	35	32	36
Bottom rib	32	27	33
<b>Viscous Criteria (m/s)</b>			
Top rib	0.58	0.51	0.79
Middle rib	0.63	0.50	0.73
Bottom rib	0.53	0.37	0.58
<b>Abdomen Total</b>			
Force (kN)	1.9	1.3	2.4
<b>Pubic Symphysis</b>			
Force (kN)	3.7	2.9	5.1

Thirdly, we will consider two simple geometry changes. The European side impact barrier has a bottom half which is 60 mm deeper than the top half (Figure 26.).



**Figure 26.** FE Model of European side impact barrier.

The first change was to extend the top half of the barrier 60 mm forward to give the barrier a planar front. The second change was to shorten the top half of the barrier by 60 mm so that the barrier bottom half was 120 mm deeper than the top half. The certification test results for the standard barrier model are near the centre of the specified corridor. Even with these changes in geometry, the barrier model still gives a total force deflection characteristic within the corridor. This shows that the effect of the geometry change on overall barrier stiffness was minimal. The effect of the geometry changes on the EUROSID injury criteria, were also small (Table 6.). Some slight improvement is seen from shortening the top half of the barrier. The most likely cause of this is the transfer of load from the load path into the occupant to the load path directly into the car.

Finally, we will consider the results of the stiffness parameter sweeps (Table 7). It is seen that stiffening the whole of the barrier increases all of the injury parameters, stiffening just the top of the barrier causes an even larger increase, but stiffening just the bottom of the barrier reduces the chest injury.

**Table 6.**  
**Injury Parameters with Varying Barrier Geometry-**  
**European Side Impact Barrier as Reference.**

Barrier Geometry	Reference (Euro)	Planar Front	Bottom half 120mm deeper than top
<b>Chest Compression (mm)</b>			
Top rib	35	33	29
Middle rib	35	34	32
Bottom rib	32	31	30
<b>Viscous Criteria (m/s)</b>			
Top rib	0.58	0.57	0.52
Middle rib	0.63	0.65	0.56
Bottom rib	0.53	0.57	0.57
<b>Abdomen Total</b>			
Force (kN)	1.9	2.1	2.0
<b>Pubic Symphysis</b>			
Force (kN)	3.7	3.5	3.2

**Table 7**  
**Injury Parameters with Varying Barrier Stiffness.**

Barrier Stiffness	Reference (EU)	Stiffness 2X	Stiffness 4X	Stiffness Top 2X	Stiffness Top 4X	Stiffness Bot 2X	Stiffness Bot 4X	Stiffness 2X	Stiffness Bot 2X
Geometry Changes:	None							Bottom half 120mm deeper than top	
Chest Compression (mm)									
Top rib	35	36	37	40	41	30	30	26	22
Middle rib	35	38	39	41	44	32	29	28	25
Bottom rib	32	36	37	36	42	30	27	28	26
Viscous Criteria (m/s)									
Top rib	0.58	0.54	0.51	0.60	0.64	0.56	0.44	0.25	0.23
Middle rib	0.63	0.65	0.64	0.60	0.68	0.64	0.54	0.40	0.38
Bottom rib	0.53	0.54	0.58	0.60	0.67	0.67	0.56	0.49	0.46
Abdomen Total									
Force (kN)	1.9	2.9	2.9	2.2	3.0	1.9	2.0	1.9	1.8
Pubic Symphysis									
Force (kN)	3.7	4.0	5.1	4.3	4.7	3.7	4.2	3.1	3.0
Barrier Peak Loads (kN)									
Barrier Bottom	85	101	115	79	71	106	120	111	111
Barrier Top	31	37	41	47	64	23	18	28	19
Barrier Total	112	128	149	124	133	126	136	127	119

If we combine this with a geometry change, i.e. shorten the top half of the barrier by 60 mm, a further reduction in the chest injury is achieved.

These results can be explained in terms of the load share between the load path into the occupant and the load path directly into the car. Stiffening the top half of the barrier increases the load through the door into the occupant and hence increases injury. In contrast, stiffening the bottom half decreases the load through the door into the occupant, by transferring load directly into the car, so reducing chest injury. For this particular car, as the middle of the barrier is approximately in line with the bottom of the pelvis, the ratio of the barrier top and bottom loads can be used as an indicator of the load share between the two major load paths (Table 7). It should be noted that in the case of stiffening the top of the barrier, there is an additional factor which could increase chest injury. This is the change in the intrusion profile from vertical to one that preferentially loads the chest.

In summary, the results of this modelling study indicate that in order to improve compatibility for side impact, the bullet vehicle should be designed such that it engages the structure of the target vehicle more effectively, through improved geometrical interaction. However, this should be achieved without compromising the intrusion profile or causing excessive roll in the target car. Stiffening of the bullet car's upper load path, without stiffening the lower path should be avoided as this will lead to increased occupant injury. It should be noted that these conclusions have yet to be validated by experimental test.

## DISCUSSION

In both frontal and side impact, it has been shown that good geometrical interaction is fundamental to compatibility. In frontal impact the effect of geometry can mask the effect of mass and stiffness and dominate the outcome. In side impact, it is seen that better structural interaction can result in lower injury criteria by transferring loads from the occupant load path directly to one directly into the car's structure.

For frontal impact it is envisaged that in order to achieve compatibility between vehicles, the frontal structure will need to have a more uniform stiffness, with better structural tie-up. This may mean that the upper load path stiffness will increase. At a first glance this would appear to be in conflict with the requirements for side

impact, but this does not have to be the case. In side impact the crush distance is small compared to frontal impact. Hence, in order to resolve the possible conflict, the upper load path of the car could have a stiffness profile that is soft for the initial crush and stiff for the remainder, satisfying both side and frontal requirements. This is not in conflict with current design, since the initial crush of cars is generally soft so that stiffer members are not deformed in low speed impacts, to meet insurance company repair ratings.

## ACKNOWLEDGMENTS

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## PROPOSAL TO IMPROVE COMPATIBILITY IN HEAD ON COLLISIONS

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Paper Number 98-S3-O-05

### ABSTRACT

All accident studies show that incompatibility has become the main cause of fatal injury. Improving compatibility is the most effective way to reduce the number of road accident victims.

Compatibility is now achievable, mainly because of improved occupant restraint systems. This paper suggests ways in which the stiffness, layout and geometry of vehicles can be improved to achieve good compatibility in frontal collisions between vehicles.

### INTRODUCTION

The problems of compatibility have already been the subject of many studies. However, these have all been limited to feasibility demonstration vehicles (CRATCH - UTH Zurich - 1996). If occupant safety is to be improved, however, it is essential to take compatibility into account during the development of current and future vehicles.

The evidence of studies conducted over the last twenty years clearly shows that solving the problems of incompatibility between vehicles is one of the most efficient ways to reduce the number of road accident victims. New regulations coming into force in the end of 1998, as well as various ratings and media tests, lead to a similar level of safety for all vehicles in a frontal impact. Even so, this performance in no way guarantees compatibility in the case of collision between vehicles. Today it is necessary not only to ensure occupant protection during impact against a fixed obstacle, but also against another vehicle.

In addition, research into compatibility must take into account the time taken to renew all the vehicles. Measures proposed for new vehicles must not create dangers for existing vehicles, otherwise the overall benefit of such measures may be severely compromised.

### RENAULT'S COMPATIBILITY APPROACH

In this case we are considering only frontal impacts between vehicles, while bearing in mind that the needs of side impact in development must also be taken into account.

Today, frontal impact between vehicles is the configuration which causes the greatest number of deaths and injuries (see the table 1). That is why it has been our main concern for several years.

#### Accidentology (France)

The French vehicle parc today comprises about:

- 25 million private cars
- 4.5 million light commercial vehicles (under 3.5 tons)
- 550,000 trucks, buses and coaches.

It is clear that up to now almost no measure has been taken to look for the differences of mass or stiffness between all these road users. It is therefore not surprising that accidents involving several vehicles represent a large share of road traffic victims.

#### Accident toll on French roads

These are the main figures summing up the situation on French roads (see Table 1).

Out of the 8,000 dead per year, around 6,000 are private car occupants. The remaining 2,000 victims are for the most part pedestrians, cyclists and motorcyclists.

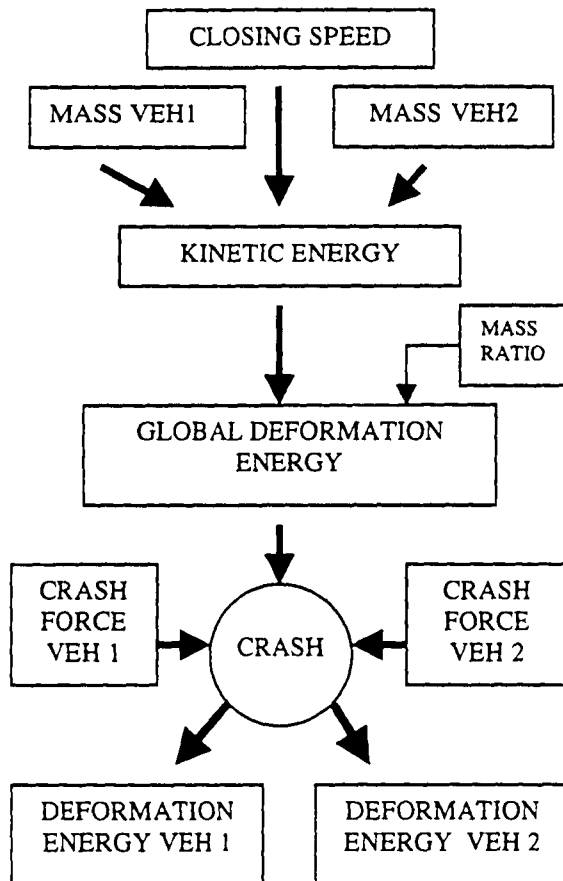
Of the 6,000 car occupants, 1,800 could have been saved if they had been wearing their safety belts. That is by far the most effective and immediate measure to limit the number of deaths.

## FUNDAMENTAL PRINCIPLES FOR STRUCTURAL COMPATIBILITY

### Theory

Compatibility between structures will depend on a correct distribution of the energy absorbed by the two vehicles. Unfortunately, no simple formula, exists to allow this distribution to be predicted. The only means of doing so are simulation, tests, and experience.

Contrary to commonly accepted ideas, mass plays no part in the way in which energy is distributed between the two vehicles. Only the stiffness, by way of the deformation loads, determines the distribution of energy between the two cars. This process is described in the following flowchart.



However, we have seen that the main cause of death is intrusion. At the same time, it is important to offer the same level of protection in both vehicles. So far as the structure is concerned, this implies that intrusion should be distributed between the two vehicles in a homogeneous manner.

The objective is to offer the same survival potential in both vehicles; in other words, any intrusion should be similar to that observed in a barrier impact at half the closing speed. This is equivalent to say that the EES (Equivalent Energy Speed) is identical for both vehicles. As a consequence, the energy absorbed by each vehicle is proportional to its mass.

*Two vehicles are compatible if they have the same EES in a car to car crash*

The following numerical example illustrates the different notions of EES and delta V:

Mass of vehicle 1 (W1): 1,000kg  
 Mass of vehicle 2 (W2): 1,800kg  
 Speed of vehicles 1 and 2 (S): 50km/hour  
 Closing speed (Cs): 100km/hour

Kinetic energy  
 $0,5 * (W1 + W2) * S^2 = 270 \text{ kJ}$

Energy to absorb  
 $GDE = 0,5 * \left( \frac{W1 * W2}{W1 + W2} \right) * Cs^2 = 248 \text{ kJ}$

Energy absorbed by vehicle 1 = compatibility energy  
 $\left( \frac{W1}{W1 + W2} \right) * GDE = 88 \text{ kJ} \gg EES = 48 \text{ km/h}$

Variation in speed Vehicle 1  
 $\left( \frac{W2}{W2 + W1} \right) * Cs = 64 \text{ km/h}$

Energy absorbed by vehicle 2 = compatibility energy  
 $\left( \frac{W2}{W1 + W2} \right) * GDE = 160 \text{ kJ} \gg EES = 48 \text{ km/h}$

Variation in speed Vehicle 1  
 $\left( \frac{W1}{W2 + W1} \right) * Cs = 35 \text{ km/h}$

Those simple calculations show that it is theoretically possible for both cars to have the same EES and that preserves the cabin space of the smaller car. Anyhow, the speed variation is still higher for the smaller vehicle by virtue of the law of conservation of momentum. The impact is always more severe in terms of speed variation for the lighter vehicle. However, the most recent occupant restraint systems allow this effect to be alleviated and we will see further that this speed

For the remaining 4,200, of all impact configurations, collisions between private cars account for 1,250 deaths, while some 1,050 result from collisions between private cars and light commercial vehicles, trucks and coaches.

These figures indicate that 55% of deaths in private cars occur in collisions with other private cars. This study will focus on this very important part of accidentology.

	Deaths	Serious injuries
Number of victims Per year in cars	6000	18000
With 100% Safety belt wearing	4200	16000
PC / PC Frontal impact	700	5750
PC / PC Side impact	520	1740
PC / PC Rear impact	30	240
PC / (LCV + HV) Frontal impact	500	850
PC / (LCV + HV) Other configurations	535	1050
total PC / PC	1250	7730
total PC / (LCV + HV)	1035	1900
Total compatibility (PC / other vehicles)	2285 (55%)	9630 (60%)

PC : Private car LCV : Light commercial vehicle HV : Heavy vehicle (French figures)

**Table 1: Distribution of deaths and serious injuries according to collision type**

### Expected gains

For collisions between vehicles and pedestrians or cyclists, representing over 1,000 victims, the only really effective measures are those which enable such accidents to be avoided (traffic separation, lower speeds in high-risk areas, future accident-avoidance systems . . .).

For the occupants of a vehicle involved in a collision with another vehicle, we have made an estimate of the possible gains with a generalisation of the best available technology in both structural behaviour and restraint systems improvement. This study also uses the statistical distribution of crash severities. A global reduction of one-third in the number of deaths and

serious injuries (see Table 2) is technically possible by taking coordinated measures on that whole vehicle range.

	Deaths	Serious injuries
PC / PC Frontal impact	350	3450
PC / PC Side impact	70	460
PC / (LCV + HV) frontal impact	225	500
PC / (LCV + HV) Other configurations	170	350
total PC / PC	420	3910
total PC / (LCV + HV)	395	850
Possible gains through improved compatibility	815 (35% of 2285)	4760 (29% of 16630)

**Table 2: Possible reduction in number of victims, by type of collision (Renault internal study)**

However, this study also shows the potential gains are not the same for each kind of accident. The two areas where the potential is the most important are the head-on collisions between two cars and the car to commercial and heavy vehicles.

For the car to car collisions, it is essential to note that in the majority of cases, cabin space intrusion is responsible for occupant death. This is why it is essential to work on structures in order to guarantee acceptable levels of intrusion. The most representative car to car collision has an overlap of 40 to 60 %. The commonly used overlap of 50% is reasonably representative of accidentology. It should also be noticed that more than 95 % of the fatal accidents occur for a mass ratio lower than 2., higher mass ratios are quite marginal.

Concerning the heavy vehicles, the figures result from a study conducted with Renault VI on the efficiency of anti under-run systems. The major effect of those systems is to put a rigid structure in face of the car in order to enable the car structure to absorb the energy of the crash. Without such a device, only the upper part of the car structures are working resulting in high intrusions for the occupant at a closing speed as low as 45 to 50 km/hour. With an optimised anti under-run system a protection can be obtained up to an impact speed of 70 km/hour.



results in a greater collapse than occurs in a barrier impact (see Figure 6).

- The second is associated with the difference in stiffness between the vehicles at the end of the impact - the main cause of incompatibility indicated by accidentology studies (Figure 8).
- The third is mainly associated with the geometry and/or structural disfunctioning: involving over-riding (Figure 9 and 10).

### Energy absorption deficiency

The energy absorption deficiency of the structures results directly from the overlapping of the frontmost elements. The energy absorbed by the frontmost elements is therefore less than occurs in a rigid wall impact.

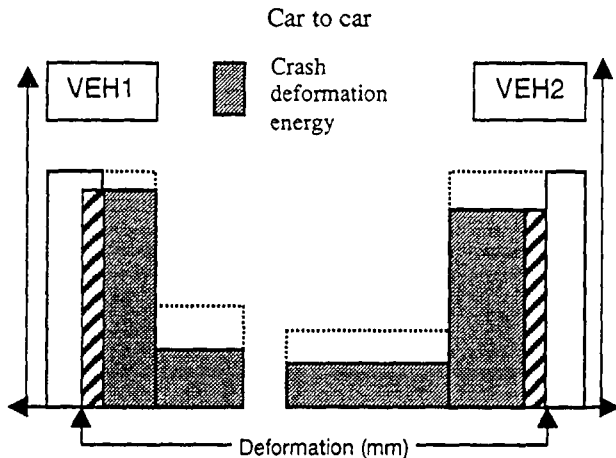


Figure 6: Energy absorption deficiency in initial car deformation

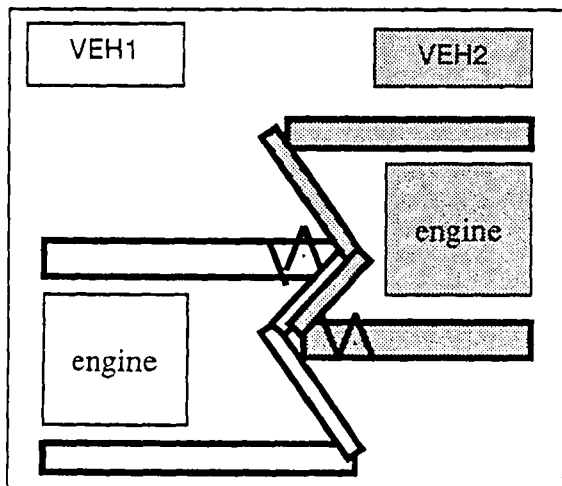


Figure 7: Geometric representation of absorption deficiency sketch in top view

### Stiffness at the end of impact

As has already been explained, stiffness determines the distribution of energy between the two vehicles. If one of these vehicles stops, because it is stiffer, then all the remaining energy is absorbed by the other vehicle. In the following example the vehicle 1, by virtue of its greater stiffness, ceases to deform, immediately resulting in a greater deformation of vehicle 2.

Car to car

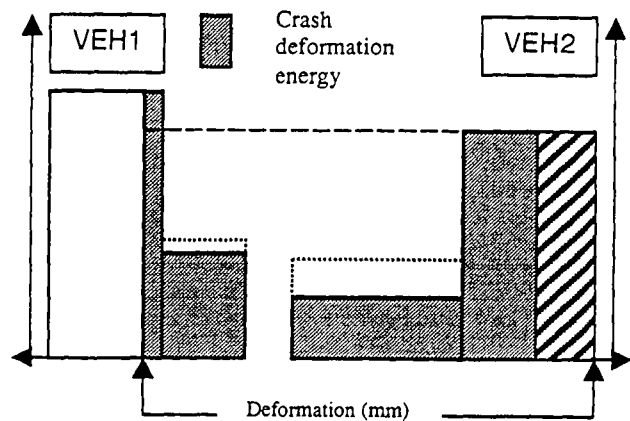


Figure 8: Incompatibility of stiffness between two vehicles

### Over-riding

Finally, we must note the existence of a phenomenon whose consequences are more serious than those of absorption deficiency: structural over-riding, in other words when one vehicle passes above the other. Figure 9 shows the energy implications of this effect.

The principle behind over-riding is relatively simple: the geometric difference after the initial impact, and the behaviour of the structures during the transition between the beginning and end of the impact event cause one vehicle to rise higher than the other.

The vehicle which is over-ridden fails to achieve its maximum load potential (since only its upper load paths are stressed). The vehicle thus achieves a much lower load resistance than the over-riding vehicle. This results in large upper-level intrusions. The most significant illustration is the difference in height between the structures of passenger cars and of heavy trucks. Accidentology studies very clearly highlight the problem of embedding or of the over-riding of the heavy truck above the passenger car. It should not be overlooked, however, that geometric incompatibilities also occur between passenger cars themselves.

variation effect is also partially reduced by the duration of the crash event. The basic principle we have proposed is theoretically possible. The major question is to design the cars so that they behave this way

### Simplified presentation of compatibility

We define the load force as the force at the interface between the car and either an opposite car or another obstacle (wall or ODB). The load levels in a vehicle during its deformation is globally increasing and can be summarised by a two stages law. The first stage is the initial load of the front structures before the engine becomes involved, and a final load after this event.

The reference we will use is a car to rigid wall crash with the same 50% offset as the car to car crash. We will compare the vehicle-to-vehicle behaviour with that of the vehicle against a rigid barrier (see Figures 4 and 5). The crash against a rigid wall is the ideal possible behaviour of the structure in terms of energy absorption, we shall use it as a reference to describe the various kinds of behaviours that can be encountered on a car to car crash.

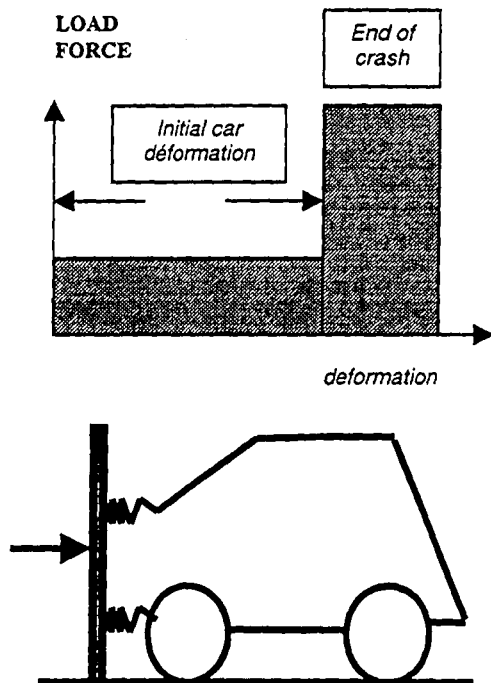


Figure 3: Laws of load/deformation of a vehicle

Let us take first the example of two vehicles in a barrier impact with a 50% offset at the same speed  $S_{686}$

We can draw the energy absorbed by each car as the surface below the force deformation curve.(Figure 4)

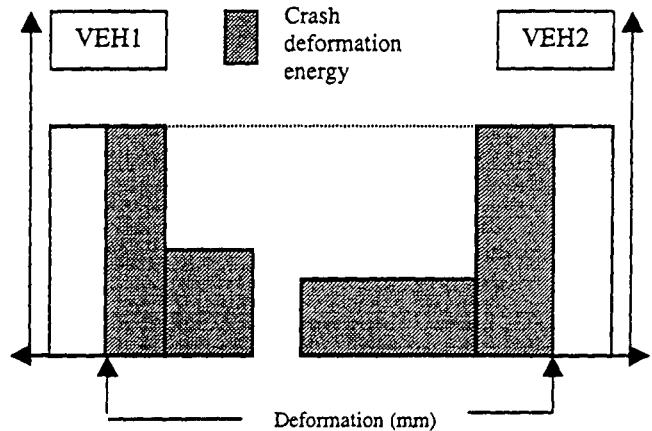


Figure 4: deformation of two vehicles against a rigid barrier

If we take the example of the same two vehicles in a head-on collision with a 50% offset at a closing speed:  $S \times 2$ . Theoretically, we can obtain exactly the same energy absorption for each car provided that the end crash force is the same for both cars (Figure 5).

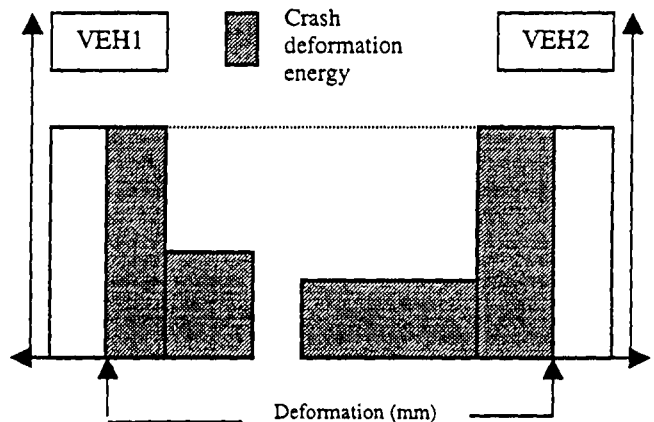


Figure 5: Theoretical compatibility between two vehicles. The collapse of the two vehicles in head-on impact corresponds to collapse in a barrier impact.

In reality, three major problems make this very difficult to achieve.

- The first is associated with the lack of a plane interface between the two vehicles, which results in an energy absorption deficiency (a reduction in the energy absorbed immediately after contact). This deficiency immediately

## THE INFLUENCE OF COMPATIBILITY ON OCCUPANT RESTRAINT

The application of compatibility to the structure increases demands on occupant retention. In the most general terms, the control of intrusion is increasing the deceleration. We shall see that the vehicle-to-vehicle configuration is not too severe for the occupants, despite the larger changes in speed for the lighter vehicle. In the 1970s the development of restraint systems was a major problem preventing structural compatibility for light vehicles to take place.

The necessary factors in achieving good retention are already well known. The progress recently achieved in series production vehicles is based on demanding improved airbag performance, in such a way as to limit load levels in the safety belt. This programmed restraint system, developed by Renault, notably allows protection for more fragile subjects [ 8 ]. In addition, it completely decouples the occupant from the vehicle. In effect, the large accelerations to which the car body shell may be subjected are not directly reflected in occupant loads.

In the light of several car to car testing, we have been able to determine that the delta-V for mass ratios up to 1.5 is not a major concern in restraint system design.

A parametric study has allowed these observations to be explained, and the influence of mass ratio, closing speed to be investigated more thoroughly. The model used takes the form of a spring-mass system. This model is based on the behaviour of an average representative car structure design.

### Model design

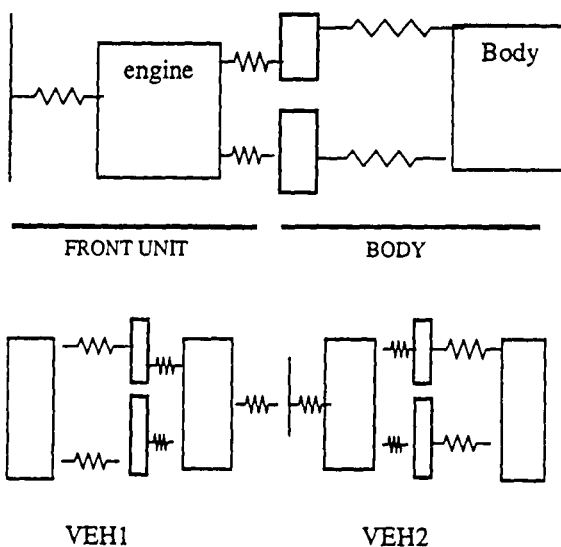


Figure 12: Spring-mass model of structure of car to car

This multi-level model is a good representation of the real dynamic behaviour in a car to car crash.

The average acceleration ( $\gamma_m$ ) of the structure changes less than the delta-V : the increase in  $\delta V$  is partly compensated by an increase of the duration of the impact event ( $t$ ).

Mass ratio		1	1,44	2
Mass 1	kg	900	900	900
Mass 2	kg	900	1300	1800
Stopping distance on wall veh 1	m	0.49	0.49	0.49
Stopping distance on wall veh 2	m	0.49	0.71	0.85
$\delta V$ veh 1	km/h	50	59	66
$\delta t$	ms	66	72	77
$\gamma_m$ veh 1 ( $\delta V / \delta t$ )	g	21.2	23.1	24.5
$\gamma_m$ evolution	%	-	9	15

Figure 13. simulation results

Therefore, the severity of a car to car crash is less important than in case of a car to rigid wall with the same delta V.

The following diagram shows how vehicle acceleration increases as a function of the mass ratio. For a reference car to car closing speed of 100 km/h, the severity for the smaller car is not higher with a 1.5 mass ratio than for a crash against an offset rigid wall at 55 km/hour.

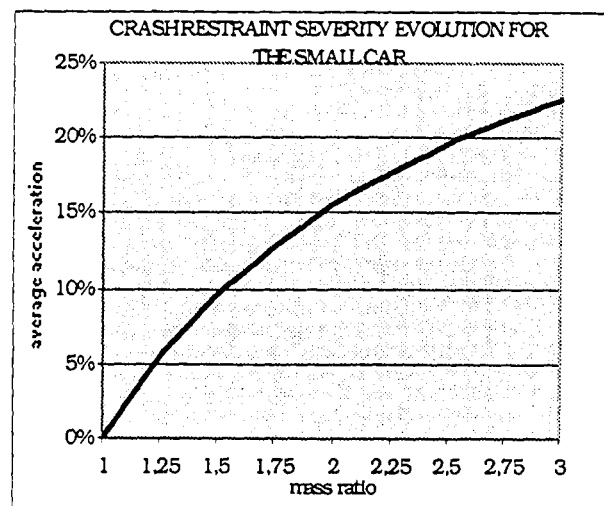


Figure 14: Change in average acceleration as a function of mass ratio

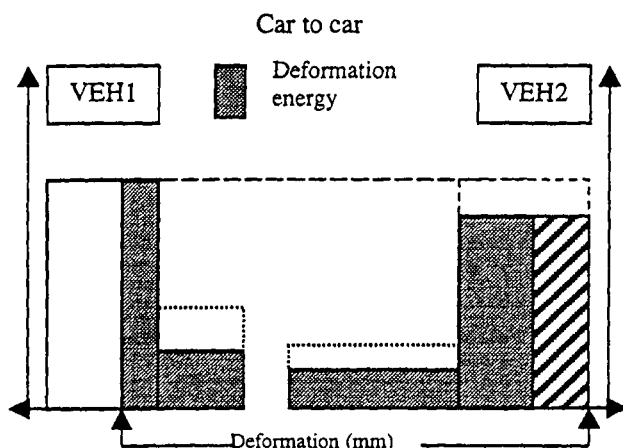


Figure 9: Energy effects of over-riding

In summary, compatibility is a problem:

- of geometry and of layout immediately after impact
- of structural behaviour during the impact event
- of stiffness at the end of the event.

### Possible improvements

#### Geometric improvements

The main concern after the impact has begun must be to ensure that the load paths work as intended. To achieve this, it is essential to distribute the initial impact load across the entire contact surface. This significantly reduces the overlapping of structures, and therefore also the energy absorption deficiency.

As a consequence, it is important to:

- increase the number of load paths
- limit the load immediately after impact
- create a front face spreading out the effort over a large surface.

From the layout point of view, it is therefore desirable to increase the number of load paths and the front contact surface, especially for the highest vehicles. The technical solutions are often very directly linked to the architecture of a car and often difficult to change

#### Improved end-of-impact load

As we have already seen, when two vehicles collide, the less stiff one absorbs more of the impact energy. The energy distribution is therefore not equal. Generally speaking, the heavier vehicle deforms less because it is stiffer in its design.

This is why a harmonisation of end-of-impact load is needed. Renault therefore proposes an end-of-impact load, which it calls the “compatibility load” of 300kN up to an EES of 55km/hour against a rigid wall or ODB (figure 10 upper view).

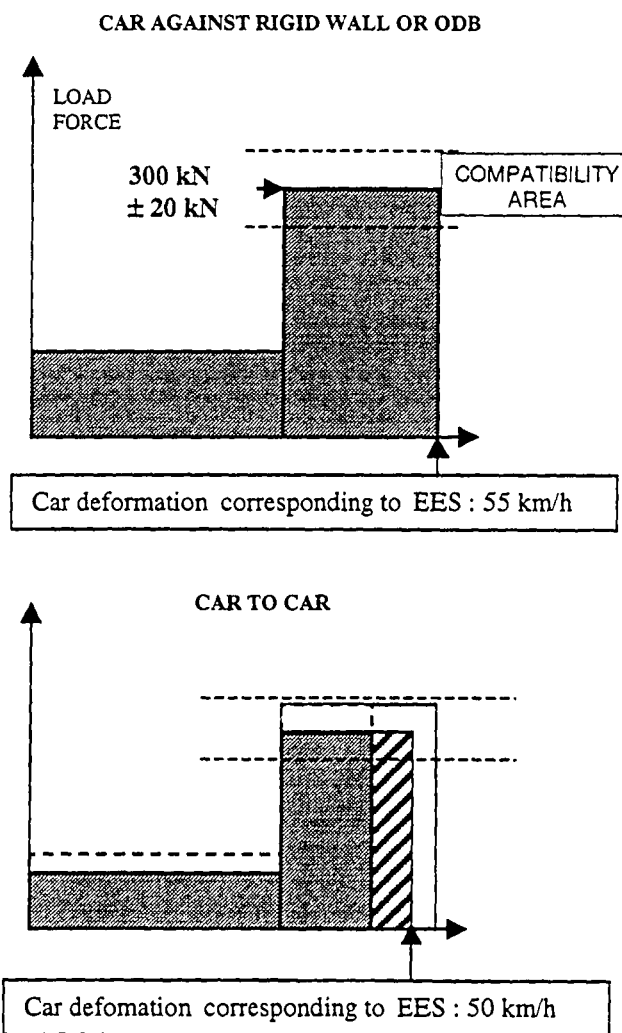


Figure 10: Compatibility load limit

We have also to define a testing procedure to control that a significant part of energy is absorbed before the car reaches the compatibility force. Else, we will have the kind of behaviour shown in figure 6 and 8.

The aim of those two procedures is to ensure that the EES of each car in the car to car test is close to 50 km/hour (figure 10 lower view). This is coherent with our fundamental principles to have the same EES on both cars, at a closing speed of 100 km/h.

## Force evaluation in vehicle-to-vehicle impact

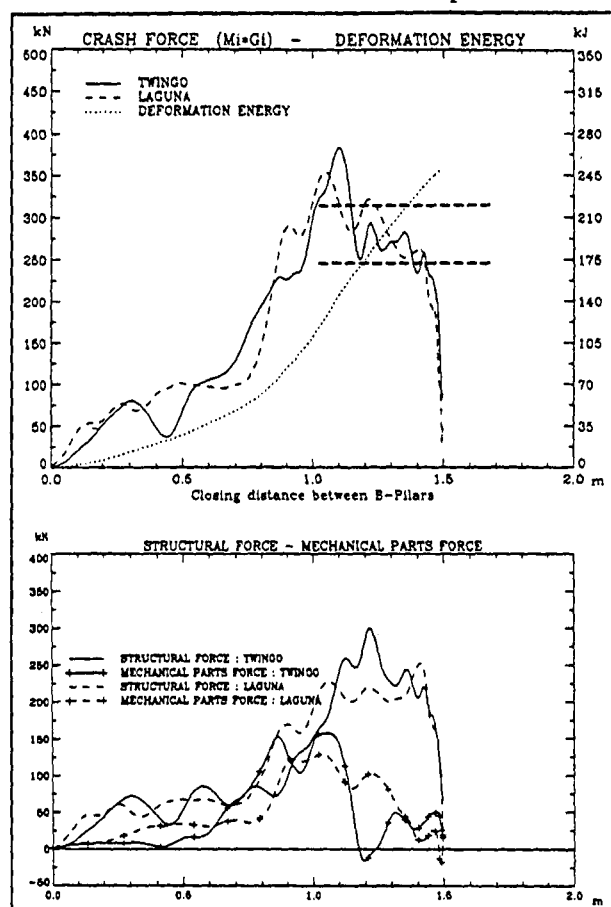


Figure 21: Results of Twingo /Laguna test

The interface force during crash was recalculated for both cars (Figure 21). The principle of action/reaction is respected. The mechanical parts interaction of both cars create a force peak that is slightly above the compatibility force. Anyhow, at the end of the crash we find a force that is very comparable to that measured on the ODB reference tests.

## Performance of the New Clio in car to car test

A good performance in compatibility was taken as a design target from the beginning of that new project. The global force capacity of the Clio in the end phase of an offset crash is at the 300 kN value we propose.

In the final development phase, we carried out 6 car to car tests against vehicles representative of the existing parc. Figures 22 and 23 show that in all cases, the two vehicles offered a good protection potential for their occupants. In two cases (VEH A and VEH B), the EES is comparable on both cars, in two cases (VEH C and VEH E), the severity of the crash is less important on the Clio II than on the opposite car. However, we observed that in the last tests against vehicle F, over-

riding began to occur with a resulting energy absorption deficiency.

The average door aperture reduction lead to the same kind of conclusions. Those results show the progress realised on this new car if we compare them with those published by the ADAC. [11]

As we indicated in the section on restraint systems, the crash severity for the restraint systems remained lower in those crashes than for a crash against an offset rigid wall at 55 km/hour.

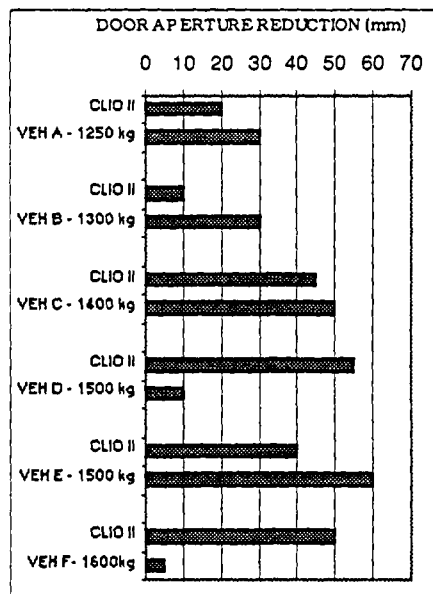


Figure 22: Average reduction of upper and lower door aperture

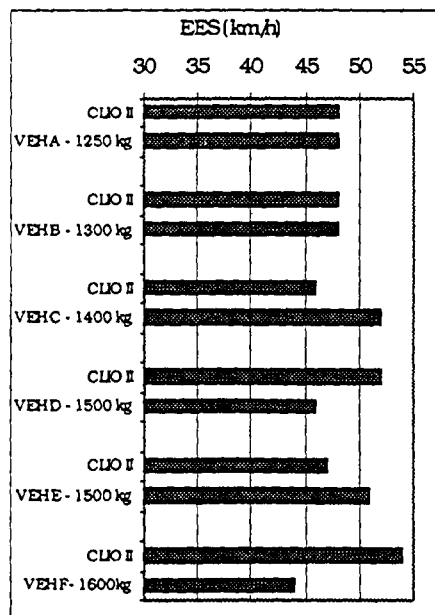


Figure 23: EES of the two vehicles

After the numerical phase, we first tested both cars on a ODB test to measure the interface force. We used also the test analysis method we developed to compute the interface force from deceleration of a set of chosen points. The results of picture 17 and 18 show both a good correlation between the force measured behind the ODB and the computed force. Further, in the end phase of the crash, both cars have a reaction force that matches the compatibility area we have defined.

#### Force measurements in the Laguna in ODB

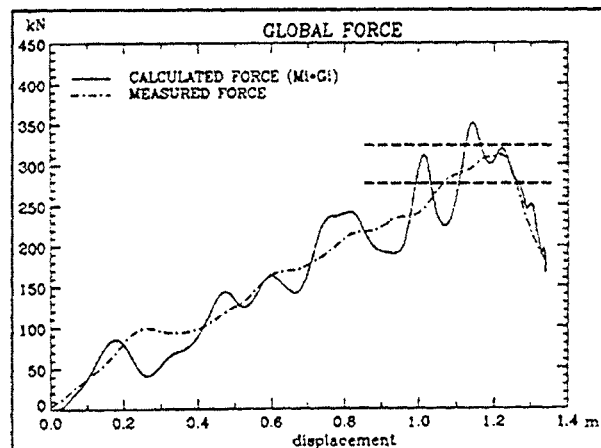


Figure 17: Comparison between measured and calculated forces

#### Force measurements for the Twingo in BFD

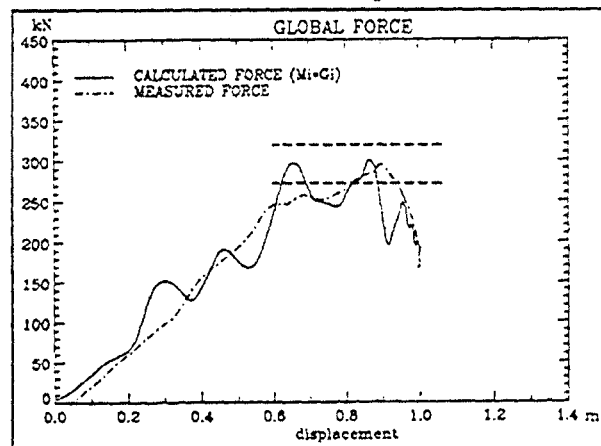


Figure 18: Comparison between measured and calculated forces

#### Global test validation at 100 km/h closing speed

STRUCTURE	TWINGO	LAGUNA
Groud speed (km/hour)	50	50
Test mass (kg)	1020	1480
Delta V (km/hour)	60	40
Kinetic energy (kJ)	98	143
Deformation energy (kJ)	105	135
EES (km/h)	50	48
Door reduction up (mm)	50	20
Doorreduction down(mm)	80	45

The global test results are in line with the expectations. The estimated EES of both cars is very close although the mass ratio is close to 1,5. The global deformation of the cars is very close to the results of the numerical simulation (figure 19 and 20)

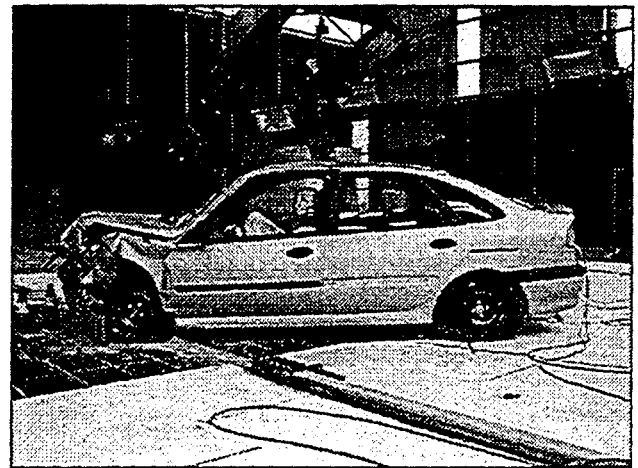


Figure 19 : Laguna after crash

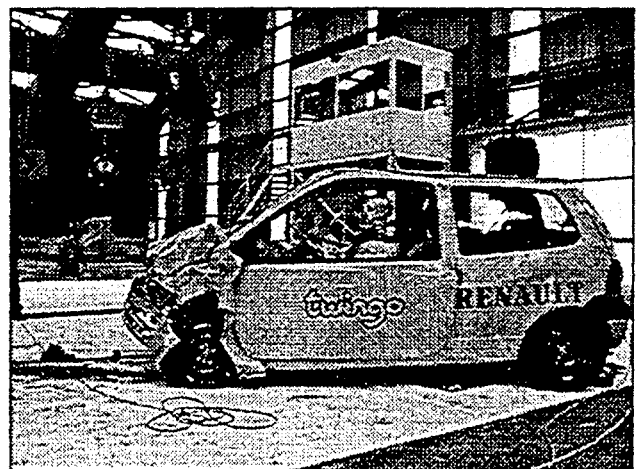


Figure 20 : Twingo after crash

#### Restraint results

RESTRAINT	TWINGO	LAGUNA
HIC	241	231
Chest acc (g 3ms)	45	40
Pelvis acc (g)	54	50
Shoulder force (daN)	440	470
Femur load (daN)	510	380

The restraint systems of both cars is a Programed Restraint Airbag working with a low force belt load limiter presented by Bendjellal 1998 [10]. That new system gives very good result on dummy valus for both head and thorax. This restraint system and the structural changes tested on the Twingo will be introduced on the new version of that car coming out in september 1998 on the European market.

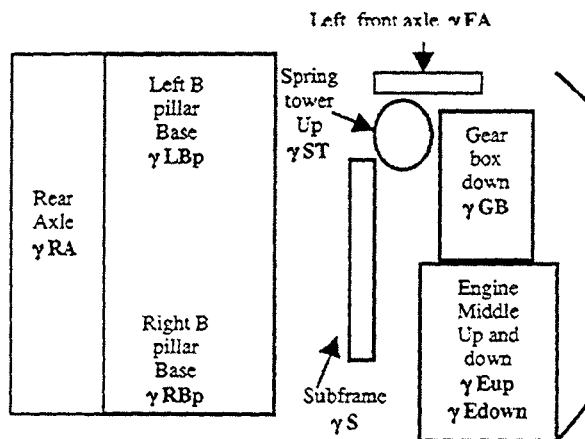
## TEST ANALYSIS METHOD

As we have already seen, it is necessary to analyse the structural crushing force in both vehicles in the case of a car to car collision. This is the reason why Renault has developed methods of evaluating this dynamic crushing force. The first method consists simply of measuring the force on a dynamometric barrier which can be used only in single vehicle crash. The second method involves evaluating the inertia forces during the impact event, while measuring the acceleration at various points in the vehicle, and multiplying these accelerations by the mass which suffers the equivalent deceleration. The sum total of all these forces therefore yields the overall crushing force acting on the vehicle during the impact.

The method is based on the principle of action and reaction. A mass represents each part of the vehicle, and of the structure. The multiplication of each of these by the accelerations gives us the forces, and the addition of these forces yields the total force.

### Measurement of the crushing force

The total force ( $F_g$ ) at the interface is made up of the inertia force associated with the mass of the parts ( $F_m$ ) and the force associated with the structure ( $F_s$ ).



We were able to verify that these two methods yield correct results for the overall crushing force, both by carrying out an impact test against a deformable barrier and comparing the two approaches, and by carrying out a vehicle-to-vehicle test in order to verify that the crushing force for the two vehicles was the same, in accordance with the principle of action and reaction.

## APPLICATION TO THE RENAULT RANGE

Work has been undertaken to apply the principles of energy compatibility to the smaller cars in the range. We have worked mainly on increasing the stiffness of these smaller cars towards the end of the impact. The results achieved are very encouraging. The vehicles concerned are the Twingo and the New Clio.

### Application to the LAGUNA/TWINGO test

According to the general principles of compatibility, we have made a first project application on the Twingo, our super mini car. We used a defined opposite car of the upper medium class, the Renault Laguna. This car has already shown in accidentology a good compatibility behaviour.

The first step was to find technical solutions to increase the stiffness of the small car. We experienced various principles using complete car FE numerical simulations. We had to put under control both the industrial feasibility and the compliance with some other rigid wall tests to prevent the car from becoming dangerous on such rigid walls.

The end result of that optimisation is presented in pictures 15 and 16. The behaviour of both cars is quite symmetrical with an important deformation of both front structures.

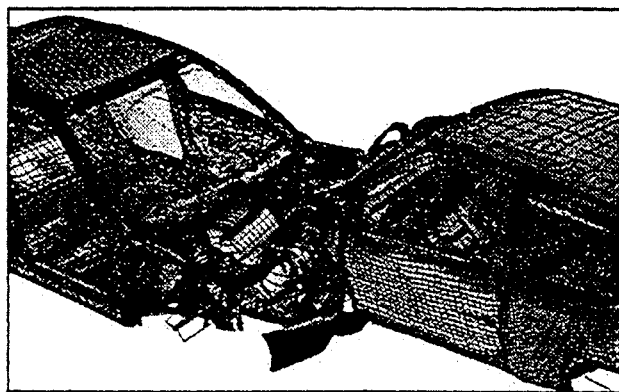
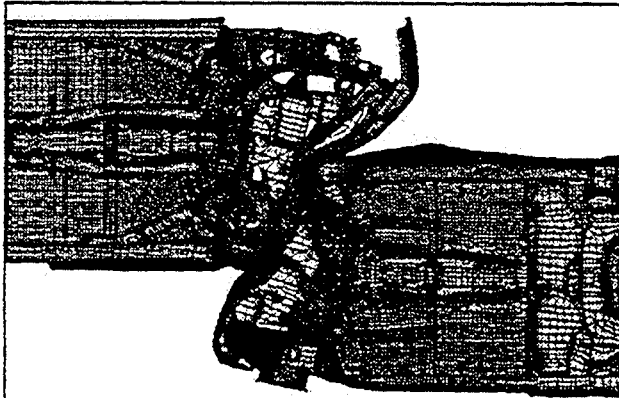


Figure 15,16 : Crash simulation



## CONCLUSION

### Proposal for a representative compatibility test configuration

No proposed improvements can be effective unless they are applied by all manufacturers and for all passenger cars. The only way to reach that target is of course to define and apply a new regulation project. Several international task forces are working in that direction. We propose here some orientations resulting from the preceding principles that can be discussed in that frame.

The two major principles for a better compatibility are to enforce a minimum resistance of the car body in the end of the crash and to put under control the energy absorption of the front end of the car.

For the first principle, testing procedures on deformable barriers have proved to be a good evaluation tool. (the crash force measured directly on a rigid wall is too sensitive to local inertia effects) It is quite easy to measure the force level behind the barrier face and to compare it with a minimum value we can call a compatibility force. We suggest that the barrier used for that purpose has a stiffness distribution that is comparable to a real car, especially concerning the vertical stiffness.

For the second principle, it is important to develop also a testing procedure to put under control the energy absorbed by each car before it reaches the compatibility force. A car designed to be very stiff can reach the compatibility force in an early phase of the crash and be very dangerous because it has not enough energy absorption capacity. The evaluation of that energy on a crash against a deformable barrier requires the capacity to evaluate the energy absorbed by the barrier. According to the strategy we have proposed earlier in this paper, the energy to be absorbed before reaching the compatibility force should also be related to the mass of the vehicle, the heavier vehicles having to absorb more energy than the lighter.

We consider at the present time that two tests are probably needed to cover the two issues of the energy absorption and the compatibility force, those two tests could be on the same barrier with two different speeds.

The increasing demands on the self protection against a rigid wall or an ODB increases dangerously the stiffness of the larger cars. We have seen that a small car can cope with the stiffness of the existing large cars but it will be extremely difficult to face a too strong increase of stiffness of those cars

This is why we have to succeed rapidly in specifying a way of evaluating and controlling that stiffness. It is

really urgent to introduce that kind of evaluation in the regulations and ratings,

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# EVALUATION OF OCCUPANT PROTECTION AND COMPATIBILITY OUT OF FRONTAL CRASH TESTS AGAINST THE DEFORMABLE BARRIER

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## ABSTRACT

Up to now crash tests highly are restricted to the aspects of self-protection. Due to the fact that compatibility is recognised as an important safety factor in real life car to car accidents a test - and rating procedure is proposed which in addition to self-protection also delivers information on the aggressiveness and compatibility of cars. The test procedure bases on the European frontal crash standard against the offset deformable barrier, but the barrier is modified towards more energy absorption and higher penetration resistance. Vehicle mass in connection with crush zone stiffness and stiffness distribution are assumed to be the influencing factors on aggressiveness, and these effects are quantified by measuring the crush force behind the barrier, the deformation energy in the barrier and the homogeneity of barrier deformation.

Several barrier tests with small and big cars are achieved. With the help of an appropriate rating system self-protection as well as aggressiveness and compatibility of the individual models are quantified. To validate these results additional frontal impacts with big cars against small cars are carried out. The findings, in terms of injury risks for the occupants of the small cars, show sufficient coincidence to the barrier results.

## INTRODUCTION

Since the 70s the total annual amount of kilometres travelled on German roads more than doubled from some 250 billion to 606 billion (1996). At the same time fatalities decreased by more than half from 21,332 to 8,758 p.a.- a development demonstrating impressively that our cars are now significantly safer. But we still register 3,801 vehicle passengers killed annually. This figure alone is a clear mandate for accident researchers, car manufacturers and the legislator as well as consumer protection organisations to further improve vehicle safety.

Accident statistics show that 49% of fatalities are related to frontal impacts, 43% to side impacts, 6% to overturning and 2% to rear-end impacts. Therefore it is essential above all to improve frontal and side impact

protection. An important key to achieve this is better compatibility of vehicle structures. In other words: vehicle compatibility needs to be improved. Big cars should not be too stiff to make them less aggressive for small cars and small cars should not be too soft in order to ensure passenger protection when hitting a big car.

It is obvious from accident statistics that the crash compatibility of different size vehicles needs to be improved. The figures of Evans/Frick [1] show for instance that the fatality rate for small vehicles in a collision with a vehicle of twice its weight is 50% higher than in a collision with a vehicle of the same weight. Ernst e.a. [2] establish an increase of some 50% also when taking into account seriously injured passengers.

No procedure exists for compatibility assessment. Even consumer protection crash tests [3] do not provide data on the aggressiveness of vehicles. Since the development of passive safety is increasingly influenced by consumer protection tests such tests should as soon as possible be extended to also cover compatibility studies. This will be all the more important as the EuroNCAP tests [4] are conducted at a relatively high impact speed and could therefore tempt car manufacturers to make heavy vehicles even stiffer and thus more aggressive.

In order to contribute to this aspect this study has the aim to examine whether the existing European frontal impact standard against the deformable barrier can be modified to generate not only information on passenger protection but on vehicle aggressiveness and thus compatibility. To get a suitable test configuration in a first step the deformable barrier and impact speed have to be adapted. Then the configuration is tested in barrier tests with several small vehicles and big family saloons. Findings on self-protection and compatibility are finally verified in selected car to car tests.

## COMPATIBILITY

Compatibility of a vehicle is defined by both self-protection and partner protection performance. A compatible car must feature good self-protection and low aggressiveness.

Good self-protection always requires high **passenger compartment stiffness** to ensure survival space for car occupants. Also **front-end stiffness** must be balanced. Therefore Baumann e.g. [5] proposes a compatibility curve based on a constant front-end stiffness for all vehicle sizes. Front-ends of the various vehicle classes would then only differ in terms of the required deformation length: 350 mm for a 700 kg car, increasing in relation to the vehicle mass up to 600 mm for 1900 kg vehicles.

From real-life accidents it can be deduced that horizontal and vertical front-end stiffness distribution should be as **homogeneous** as possible. Overriding is particularly dangerous and can be prevented by good vertical stiffness distribution.

Figure 1. gives an overview of compatibility measures and their effect on self-protection and aggressiveness for front and side impact and overriding. This shows that all measures in most cases have a positive or at least indifferent effect on self-protection and aggressiveness. There could be an aggressiveness increase for side impacts where small vehicles would have to be reinforced with the aim to achieve a balanced front-end stiffness for frontal impacts.

compatibility measure	frontal impact		side impact		under-riding
	self protection	aggressiveness	self protection	aggressiveness	
high compartment stiffness	+	0	+	0	+
balanced crush zone stiffness	+...0	+	0	-...+	+...0
homogenous horizontal crush zone stiffness distribution	+	+	0	+	+
homogenous vertical crush zone stiffness distribution	+	+	0	+	+

small...big car      + positive effect  
0 indifferent  
- negative effect      small...big car

**Figure 1. Compatibility measures and their effects on self protection and aggressiveness**

On the basis of the above compatibility measures two important statements can be made on compatibility assessment:

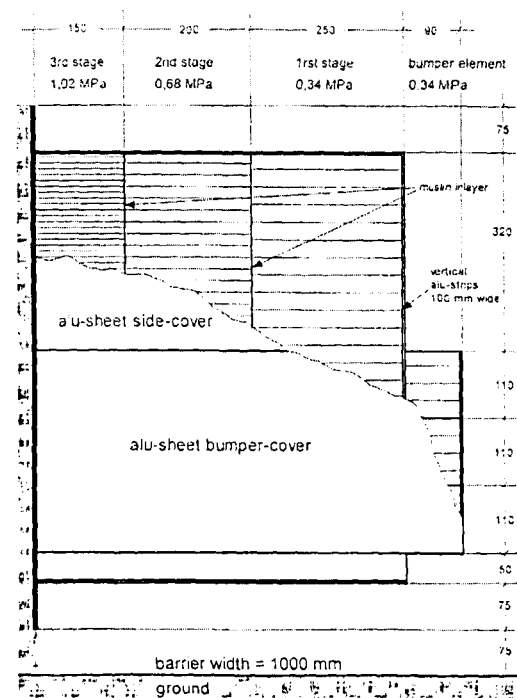
- Limitation to just one criterion is not enough.
- The applied test procedure in addition to self-protection must also provide findings on front-end stiffness and its horizontal and vertical distribution.

Front-end stiffness primarily effects the energy and force transmitted to the other vehicle. Stiffness distribution determines the degree of plane or local force transfer. The following is a description of how to develop the European (EEVC) barrier in order to get results on these aspects on the basis of its force and deformation performance.

## DEFORMABLE BARRIER

As described in paper [6] the EEVC barrier has some weaknesses and is therefore not suited to achieve the objective of gaining compatibility results from frontal impact tests. Its energy absorption and penetration resistance are quite low specially for higher impact speeds than the coming European standard. Some vehicles crash through the barrier and hit the wall behind the barrier. This causes an increase of collision intensity for heavier vehicles at identical impact speed and with growing vehicle mass. Also no conclusions are possible as to energy and force transmission. Penetration against the wall favours vehicles with local stiffness concentrations with respect to the bridge effect of the wall.

The described shortcomings can be avoided by the three-layer barrier with stepped stiffness (Figure 2.). Energy absorption capacity is 2.5 times that of the EEVC barrier. The multi-layer feature ensures a far greater penetration resistance. Force measuring devices behind the barrier allow for registration of the force transmitted by the test vehicle during impact. Here in particular 9 load cells are used to measure total force and to a certain extent also force distribution.

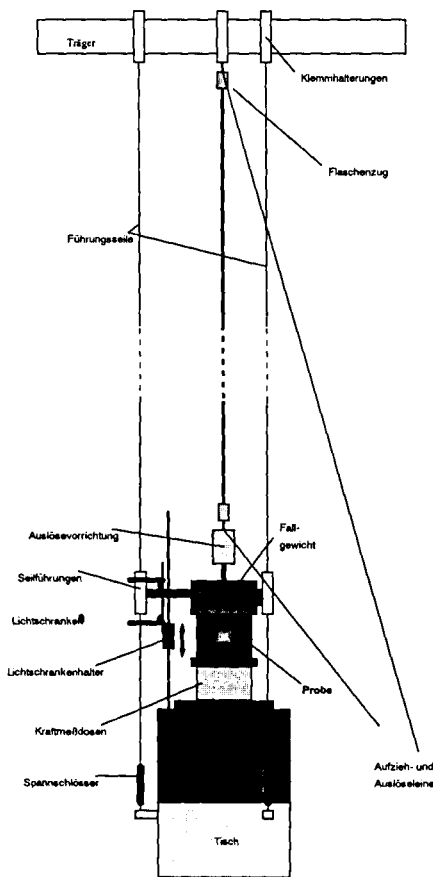


**Figure 2. Improved barrier with higher energy absorption and penetration resistance**

Energy absorbed by the barrier is determined with the following formula:

$$E_{\text{barrier}} = \sum_{j=1}^7 \sum_{i=1}^{10} \left\{ P_{dyn1} (\bar{x}_{\text{barrier}_{ij}} + \bar{x}_{1_{ij}}) + P_{dyn2} \bar{x}_{2_{ij}} + P_{dyn3} \bar{x}_{3_{ij}} \right\} \cdot A_{ij}$$

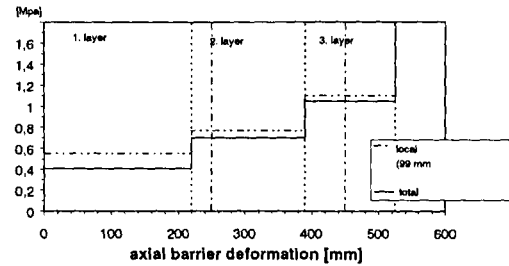
$P_{dyn1,2,3}$  are the dynamic barrier stiffnesses of the layers 1,2,3. The bumper stiffness is identical with the stiffness of the first layer. A grid divides the barrier front surface horizontally into  $i = 10$  and vertically into  $j = 7$  surface element rows.  $A_{ij}$  are the areas of the surface elements  $ij$ .  $\bar{x}_{\text{barrier},1,2,3_{ij}}$  are the axial displacements of surface elements  $ij$  within the bumper respectively the layers.



**Figure 3. Test bench for proving dynamic barrier stiffness**

Dynamic barrier stiffness is determined in a falling mass test, Figure 3.. The measurements are carried out in dependence on impact speed and element displacement. The results show that stiffness increases with raising speed. For 10 m/s the first layer stiffens up from 0,34 to 0,39, the second from 0,68 to 0,71 and the third layer from 1,02 to 1,04 MPa, Figure 4.. The measurements only have been achieved up to this speed. It is expeted that there will not be significant further raise for higher impact speeds. But the

findings should be proved on a test sled where the deformations can be brought into the barrier more realistically than with the falling mass.



**Figure 4. Dynamic barrier stiffness for impact speeds > 10 m/s**

## IMPACT SPEED

### Objectives

Currently vehicles tend to be designed for ensuring good occupant protection in a collision with a vehicle of the same weight. However, as in real life small vehicles far more frequently collide with bigger cars than with those of their own size, smaller vehicles generally experience a higher collision intensity in a car to car collision. In a real-life accident the smaller car is subject to a stronger impact and should therefore undergo stricter testing.

This raises e.g. the question with which speed a small car should be run against the barrier in order to simulate a real-life impact at 50 km/h against a big family saloon. This configuration would cover about 85 % of all real life frontal collision severities for the small car.

### Test procedure

First assessments indicate that 3 tests would be useful to identify the appropriate impact speed:

- Small car at 56 km/h against barrier with 40% offset
- Small car at 64 km/h against barrier with 40% offset
- Small car at 50 km/h against big family saloon with 50% offset.

The small car used was the Ford Ka (test weight 1230 kg) and the big car the Mercedes E (test weight 1665 kg). The two cars were selected since they are relatively new on the market and are said to have already been constructed with a view to compatibility aspects. The cars were equipped with two 50% Hybrid III dummies in the driver and rear right passenger position and two 18 kg cubes in the boot, according to DIN 75410-2.

### Injury Severity

From the test results injury risk marks for Ford Ka

occupants are determined on the basis of the rating procedure described in the next chapter. Figure 5. gives a comparison of the three tests showing that the 56 km/h impact against the barrier produces the lowest and the Mercedes E impact the highest injury risk. In average the Ka driver risk marks for the 56 barrier test are 0,7 points lower and for the 64 test 0,3 points lower than for the test against the Mercedes. In other words the 64 barrier test is a little bit less severe but quite close to simulate an impact of a small car against a family saloon with 50 km/h.

car model Testcode	Ford KA 5 K 0297 FO	Ford KA 6 K 0297 FO	Ford KA E-K 297 FO	injury risk difference KA/barrier-KA/Mercedes	
V <sub>crash</sub> [km/h]	56,2	64,1	50,2	56/50km/h	64/50km/h
	against deformable barrier	against deformable barrier	against Mercedes E		
overlap [%]	40	40	50	40/50	40/50

#### DRIVER

body part	risk mark	risk mark	risk mark	risk mark difference	
head	2,7	2,7	3,2	-0,5	-0,5
neck	2,1	2,3	2,4	-0,3	-0,1
arms	3,2	4,3	4,5	-1,3	-0,2
thorax	2,4	2,4	2,8	-0,4	-0,4
abdomen	1,3	1,3	1,5	-0,2	-0,2
pelvis	1,9	2,3	4,0	-2,1	-1,7
legs	3,6	4,4	3,7	-0,1	0,7
injury risk	2,5	2,8	4,0**(3,2)	-0,7	-0,3

rescue risk	3,5	3,7	3,8	-0,3	-0,1
total risk	2,8	3,0	4,0**(3,3)	-0,6	-0,3

#### REAR SEAT PASSENGER

head	1,9	2,1	2,5	-0,6	-0,4
neck	2,4	2,5	2,6	-0,2	-0,1
arms	1,0	1,1	1,0	0,0	0,1
thorax	2,2	2,3	2,2	0,0	0,1
abdomen	1,3	1,3	1,5	-0,2	-0,2
pelvis	1,5	1,6	1,9	-0,4	-0,3
legs	1,2	1,5	1,5	-0,3	0,0
injury risk	1,6	1,8	1,9	-0,2	-0,1

rescue risk	3,9	4,0	4,0	-0,2	0,0
total risk	2,2	2,4	2,4	-0,3	-0,1

Figure 5. Injury risk marks for Ford KA occupants

### Collision Severity

For the 56 barrier test the deformation energy in the barrier is 30,08 kJ. Assuming rebound energy being 10% of the original kinetic energy the energy absorbed by the Ka is calculated to 103,9 kJ. A Ka to Ka impact with 50 km/h would create an energy absorption of 106,8 kJ in the KA. This shows that the collision severity of the 56 barrier test is very close to the 50 km/h car to car test with vehicles of the same weight.

For the 64 barrier test the deformation energy in the barrier is 44,97 kJ, and the absorbed energy in the Ka is calculated to 129,9 kJ. For a Ka impact against a vehicle with the Mercedes E weight the absorbed energy in the Ka highly depends on the stiffness ratio of the two cars: In the case that the two cars have the same stiffness (compatibility demand in [5] for future vehicle design) the absorbed energy is calculated to 122,8 kJ, if the stiffnesses are

proportional to the vehicle masses (approximately today's standard design) the absorbed energy is calculated to 141,2 kJ. From this the 64 barrier test also shows little less severity than demanded to resist today's bigger vehicles but seems a acceptable compromise for next future.

### Sum Up

Assuming that the aggressiveness of big vehicles will be reduced for compatibility purposes 64 km/h seems to be the appropriate speed for small cars in order to simulate the 50 km/h impact against big cars.

Under the objective to simulate a 50 km/h car to car impact generally a mass-related impact speed as shown in Figure 6. is proposed. Small vehicles should be tested with 64 km/h to simulate impacts against much bigger models, and very big cars such as mini busses should be tested with 56 km/h to simulate impacts against itself. Reducing the impact speed with increasing vehicle mass will enable car manufacturers to design heavy cars with a softer front-end structure and thus make them more compatible.

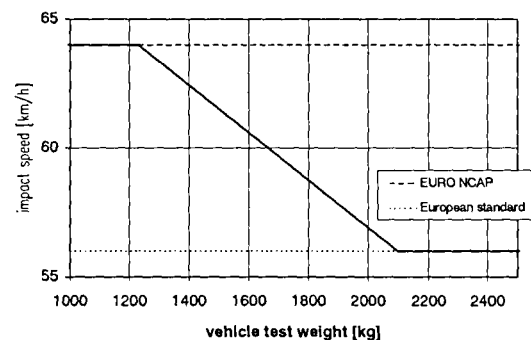


Figure 6. Mass depending impact speed

### SELF-PROTECTION AND COMPATIBILITY STUDY BASED ON BARRIER TESTS

#### Objectives and test procedure

This chapter will attempt to provide information on self-protection, aggressiveness and compatibility from frontal impact tests against the barrier. The test vehicles are current volume models of two different weight classes.

Small car	Citroen Saxo Fiat Punto Ford Fiesta Ford Ka Mitsubishi Colt
Big family saloon	BMW 520i Lancia k Mercedes E 220D Volvo S70 2.0

All vehicles are tested in a 40% offset frontal impact against the barrier. As explained in chapter before the impact speed for small cars is 64 km/h and for big family saloons 60 km/h. The cars are occupied by two 50% Hybrid III dummies in the driver and rear right passenger positions and have two pieces of luggage in the boot in conformity with DIN 75410-2. For registration of the force transmitted from the vehicle to the barrier 9 load cells are placed between the barrier and the impact block.

## Self-protection rating procedure

This procedure is used to determine the risks for the occupants. The total risk is a combination of the **injury risk** and the **rescue risk**, Figure 7..

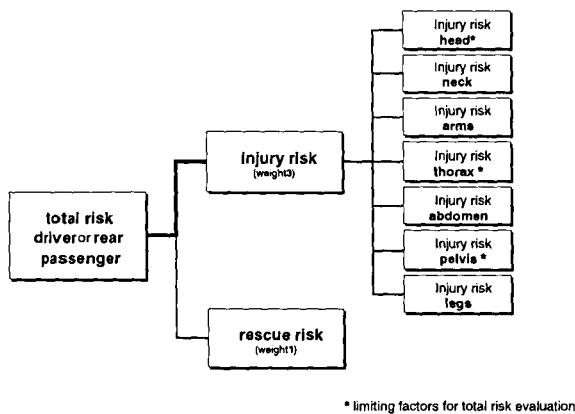


Figure 7. Diagram for total risk rating

**Injury risk:** Assessment of the injury risk is based on a body part related rating system. Risk marks are identified for individual body parts. Generally the injury risk mark for the driver and rear passenger is the arithmetic mean of all body part risk marks:

$$mark_{driver, passenger} = \sum_{head}^{legs} mark_{body\_part} / 7$$

But where a biochemical limit for the central body parts head, thorax or pelvis is exceeded there will be a down-valuation to the mark of the respective body part.

Body part marks are composed of the marks for individual criteria. Figure 8. shows a list of the applied individual criteria and their allocation to the body parts. There are primary and secondary criteria. Primary criteria always head the list and are printed in **bold**, secondary criteria are listed below and printed in *italics*.

As a rule only primary criteria marks are used to make up the body part mark. Secondary criteria serve as modifiers and will only be considered where this will

generate poorer body part marks than the result from primary criteria. [7] gives a detailed description of the body part related rating system.

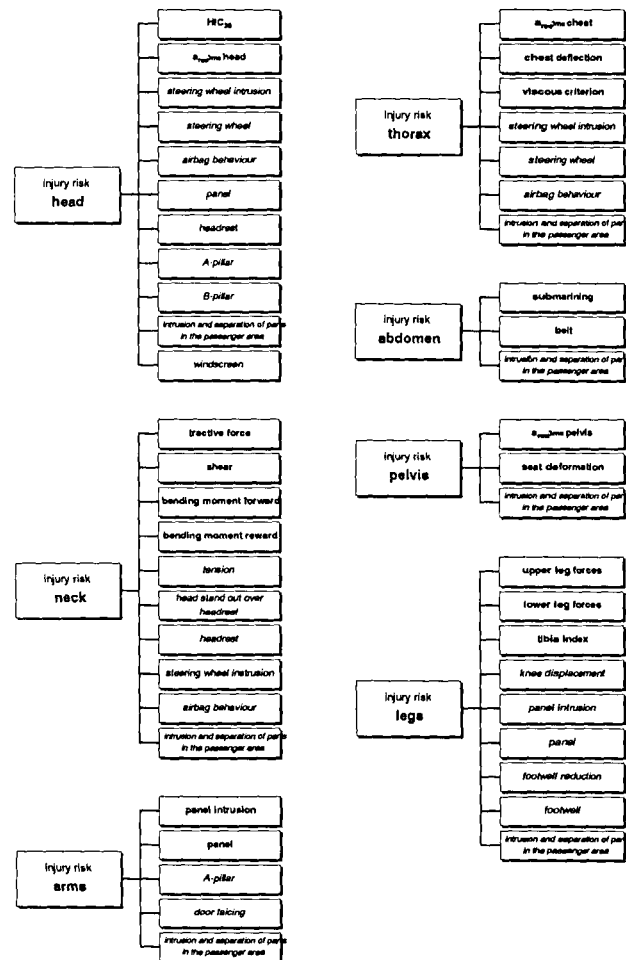


Figure 8. Diagram for body parts injury risk rating

**Rescue risk:** Figure 9. gives an overview of the assessment criteria for the rescue of occupants of a crashed vehicle. As for injury risk rating the rescue risk total mark is composed of primary and secondary criteria [8].

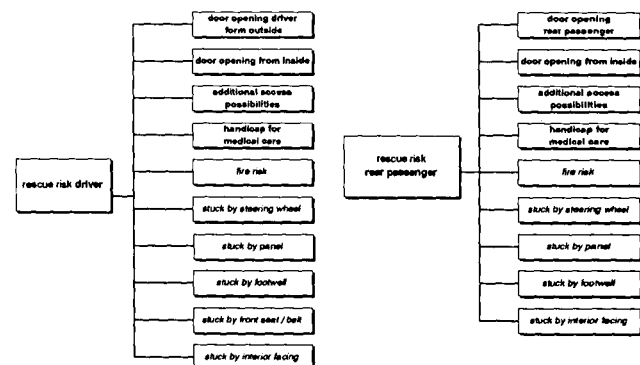
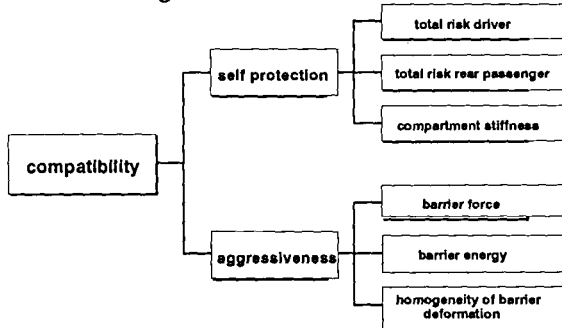


Figure 9. Diagram for rescue risk rating

## Compatibility rating procedure

As explained vehicle compatibility is determined both by self-protection performance and aggressiveness [9]. The compatibility rating diagram based on this definition is illustrated in Figure 10..



compatibility mark = worse mark out of self protection an aggressiveness

Figure 10. Diagram for compatibility rating

Only high level self-protection and partner protection performance ensure vehicle compatibility. However, partner protection and thus aggressiveness improvements must not result in a deterioration of the self-protection level. Therefore the compatibility mark is defined not to be better than the worse mark from the two main criteria self-protection and aggressiveness.

## Self-protection

Assessment aspects for self-protection are summarised in risk marks are calculated as explained in chapter 5.2. Passenger compartment stiffness is used as an additional

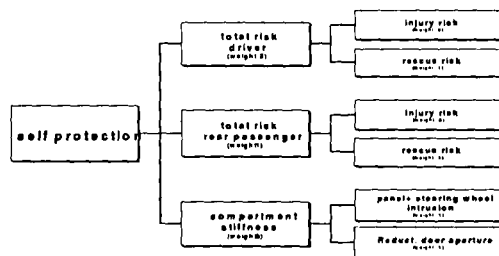


Figure 11. Diagram for self-protection rating

parameter for self-protection assessment (Figure 11.). The mark for compartment stiffness is composed of the horizontal intrusion of the panel and steering wheel and the reduction of the driver door aperture. In order to get precise data targets are affixed to the defined measuring points. There will be measuring before and after the impact. Two mean values are generated from the differences:

1. **Intrusion** mean averaged from horizontal intrusions of the measuring points

- panel far left
- panel left of steering column
- panel right of steering column
- panel left of centre console
- steering wheel center.

2. **Door aperture reduction** mean averaged from aperture reductions of measuring points

- lower rim door window level
- horizontal door lock level
- horizontal door sill level.
- diagonal bottom left to top right.

The resulting mean values are marked on the basis of the scale shown in Figure 12.. This will generate a mark for both intrusion as well as for the reduction of the door aperture, the total mark for compartment stiffness is then established in a 3:1 ratio.

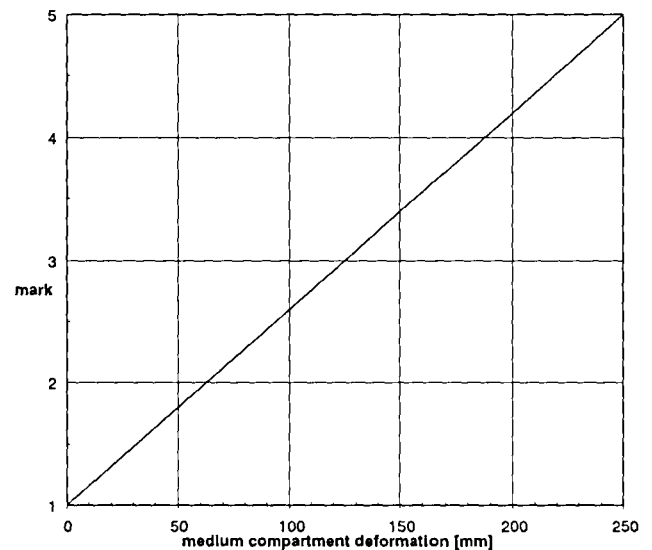


Figure 12. Scale for compartment stiffness

## Aggressiveness

Figure 13. shows the diagram for aggressiveness rating. There are the following three main criteria:

**Barrier force:** For crash testing force measuring devices are placed behind the deformable barrier for registration of the forces impacting the collision partner - in this case the barrier. Rating is based on the maximum value and the total force mean established for a period of 200ms. Figure 14. shows the marking scale for maximum and mean barrier forces.

**Barrier energy:** From axial barrier surface element displacements the energy absorbed by the barrier is determined according to the formula described in chapter "barrier". Translation of this energy to the rating mark is done on the basis of the scale shown in Figure 15..

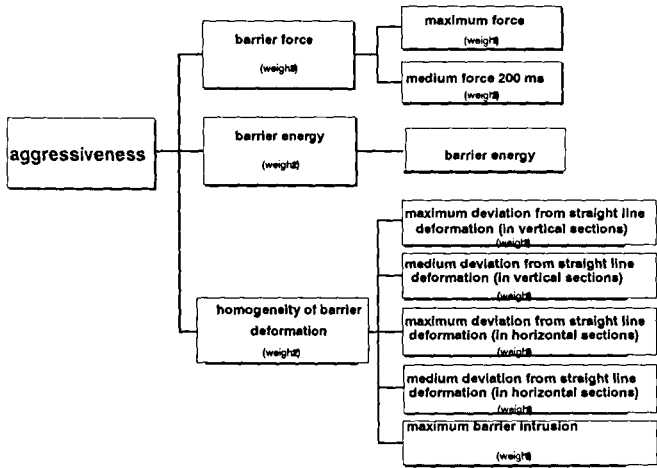


Figure 13. Diagram for aggressiveness rating

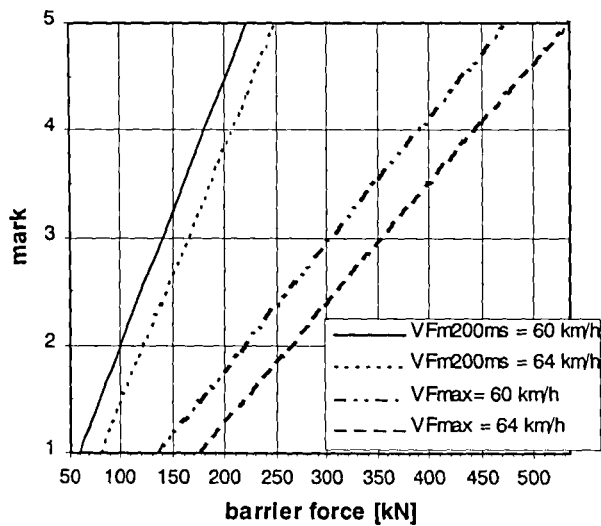


Figure 14. Scale for maximum and medium barrier force

**Homogeneity of front-end stiffness:** From the deformation pattern it can be read whether the front-end allows for extensive mutual cover and support (shield function) or penetrates the barrier deeply due to stiff protruding vehicle components. For quantification of such homogeneity the horizontal and vertical sections of the deformed barrier surface are examined on the following criteria, Figure 13.:

- maximum deviation from correlation straight line deformation in horizontal direction

- mean deviation from correlation straight line deformation in horizontal direction
- maximum deviation from correlation straight line deformation in vertical direction
- mean deviation from correlation straight line deformation in vertical direction
- maximum intrusion.

Figure 16. shows the marking scales for these homogeneity criteria.

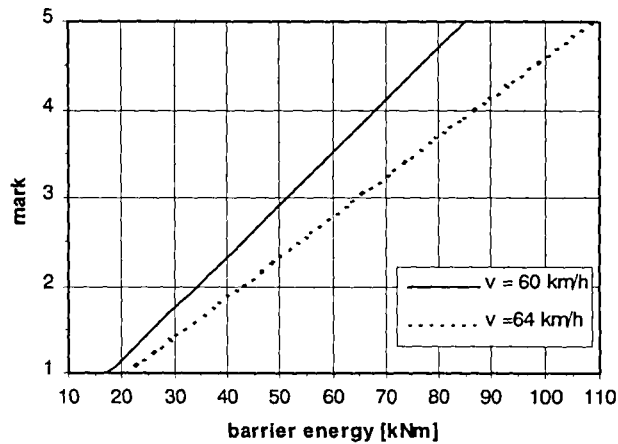


Figure 15. Scale for barrier energy

### Findings

Results from barrier tests are translated into assessment marks on the basis of the rating procedures explained before. The findings are presented in Figure 17..

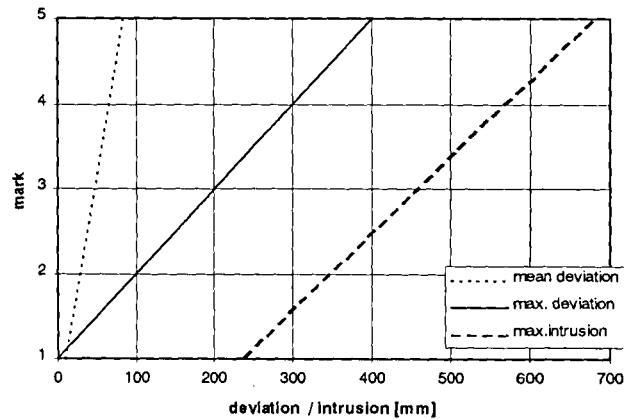


Figure 16. Scales for barrier deformation

	weight	small size cars					upper mid size cars			
		Citroen Saxo	Mitsubishi Colt	Fiat Punto	Ford Fiesta	Ford Ka	Lancia k	Volvo 520	BMW 520i	Mercedes E
total risk driver	2	4,5	3,2	3,9	2,8	3,0	3,8	2,0	1,8	1,7
total risk rear passenger compartment	1	2,8	4,8	2,7	2,6	2,4	1,8	1,8	1,3	1,5
stiffness	2	4,7	3,9	4,3	3,3	3,5	4,4	1,8	1,6	1,5
self protection		4,5	3,8	3,9	2,8	3,1	3,8	2,0	1,8	1,7
self protection mark cannot be better than total risk driver mark (limiting factor)										
barrier force	3	1,2	2,0	1,6	1,8	1,7	2,9	3,1	2,8	3,2
barrier energy	2	1,2	1,4	1,3	1,5	2,1	2,5	2,4	2,5	3,2
homogeneity of barrier deformation	2	2,5	4,1	1,9	3,7	3,0	2,3	2,3	2,4	3,0
aggressivity		1,6	2,4	1,6	2,3	2,2	2,6	2,7	2,6	3,1
compatibility		4,5	3,8	3,9	2,8	3,1	3,8	2,7	2,6	3,1
compatibility mark = worse mark out of self protection and aggressivity										

Figure 17. Compatibility rating for small cars and big family saloon cars.

The above table illustrates that the self-protection and partner protection performance for the **Citroen Saxo** is rather unbalanced. Resistance at the barrier is too low which has a very negative influence on self-protection. In this test series energy transmission to the barrier is lowest for the Saxo (25 kJ). Also behind the barrier the lowest forces by far are measured. While aggressiveness is low for the Saxo this unfortunately has a fatal effect in terms of self-protection. Because of a too low deformation resistance it absorbs most of the energy itself. At the same time the greater part of the energy is transferred to the passenger compartment which is too weak and collapses totally. For the driver this presents a lethal injury risk. In view of the poor self-protection performance the Saxo is a vehicle with low compatibility.

Like the Saxo the **Fiat Punto** has no sufficient balance between self-protection and partner protection. The low energy input in the barrier (27 kJ) and low reaction forces prove the gentle treatment of the collision partner. From the extensive and balanced deformation of the barrier it can be seen that front-end stiffness distribution of the Punto is very homogeneous. But passenger compartment stability is far too low. Most of the impact energy is transferred to the passenger compartment which means considerable reduction of the driver's survival space. This increases the total risk for the driver and is finally reflected by the relatively poor compatibility mark.

Front-end and passenger compartment stiffness is far more balanced for the **Ford Fiesta**. In terms of partner protection only the non-homogeneous front-end stiffness distribution is to be criticised. The longitudinal is still too stiff in the front section and penetrates the barrier deeply. But the passenger compartment is still stable enough to resist the forces transferred via the longitudinals relatively well. The passenger compartment of the Fiesta shows the least deformation of the small cars tested. This also has a positive effect on the passenger injury risk. As self-protection is on the whole still rated slightly lower than partner protection this is reflected by the compatibility mark. The Ford Fiesta therefore gets a satisfactory compatibility rating. Improvement potential is seen in the

deformation performance of the longitudinals. Stability of the passenger compartment could also be improved in order to further reduce the injury risk for passengers.

The **Ford Ka** demonstrates that its partner protection is slightly more developed than that of the Fiesta. Particularly the Ka's front-end stiffness distribution is far more balanced. The modern front-end structure with stable front longitudinals prevents deep penetration of the barrier. However, on the whole the longitudinals are still too stiff and penetrates - if on a broad surface - the barrier very deeply. Thus the Ford Ka transmits far more energy to the collision partner than the other vehicles tested, but this will be an advantage in a crash with a heavier vehicle. Since self-protection rating of the Ford Ka is not as high as for partner protection its compatibility performance can only be graded satisfactory. Particularly in terms of driver survival space the passenger compartment still has some weaknesses. Driver injury risk in the Ford Ka is slightly higher than for the Fiesta. Still, the Ka with its modern design gives the best examples for what compatible vehicles could be like.

Performance of the **Mitsubishi Colt** is much poorer. Serious self-protection deficits are reflected by the compatibility mark. The passenger compartment is so massively deformed that the driver's survival space is dangerously reduced. Due to insufficient securing of the rear seat back rest especially rear seat passengers may suffer lethal injuries. But the Colt also has partner protection weaknesses. The barrier deformation pattern clearly illustrates that front-end stiffness is very unbalanced. The longitudinal is far too stiff, hardly deformed in comparison with the adjacent components and penetrates the barrier deeply. A positive aspect is the low energy transmission to the collision partner. The Mitsubishi Colt gets a low compatibility rating because of the poor self-protection performance.

The self-protection level of the **BMW 520i** is very high. The risk for both occupants is clearly in the non-critical range. The passenger compartment shows hardly any deformation. Despite the lower impact speed the greater mass aggressiveness of the, in comparison to the small cars, much heavier vehicles is clearly noticeable in partner protection performance. Although the reaction forces measured behind the barrier are higher relatively low remaining forces are identified for a car of this weight class. The energy transferred to the collision partner is quite low. Front-end stiffness distribution is also relatively homogeneous. The stable aluminium cross rail keeps the front end firmly together and helps to ensure the evenly sloped deformation pattern. Only in the lower section some chassis parts protrude aggressively from the body contour. The BMW 520i gets a rather acceptable compatibility mark.

The result for the **Lancia k** is much poorer. The serious self-protection deficits are reflected by the compatibility mark. There is a high risk mainly for the



driver. His survival space is significantly reduced by the massive deformation of the passenger compartment. The Lancia's partner protection performance is better. The forces measured behind the barrier are slightly higher than for the BMW but the Lancia transmits slightly less energy to the collision partner. Front-end deformation is very balanced and shows no local aggressiveness. Also the lateral stability of the front-end structure indicates a homogeneous stiffness distribution. Despite the good partner protection performance the Lancia k is rated poor for compatibility due to inadequate self-protection.

The **Mercedes E** has the best results for self-protection of the whole series. The passenger compartment is the most stable and shows only minor deformations. For both occupants the total risk is very low. For partner protection, however, it does not reach fully the level of the test competitors. In a crash the highest reaction forces behind the barrier are measured for the Mercedes, and it transmits considerably more energy to the collision partner. The deformation pattern of the barrier clearly illustrates that front-end stiffness distribution is not optimal. Because the front longitudinals are very stiff the front crossrail shows a stepped deformation pattern. This increases the risk of interlocking of the parties involved in a real-life accident. Due to such partner protection behaviour the Mercedes E can only be rated satisfactory for compatibility.

The **Volvo S70** does not quite achieve the self-protection level of the BMW or Mercedes. Deformation of the passenger compartment is slightly worse. But the risk for the two occupants is still clearly in the non-critical range. In partner protection performance the advantages of the state-of-the-art design of Volvo become obvious. The front-end structure is supported by four longitudinals and is kept together by a stable aluminium box-section crossrail. Due to this homogeneous stiffness distribution the front end can deform evenly on a broad surface which is reflected by the evenly sloped deformation pattern of the barrier. And the Volvo transmits even less energy to the collision partner than the Lancia.

The Volvo S70 gets a rather acceptable compatibility mark.

## VERIFICATION OF COMPATIBILITY FINDINGS BASED ON CAR TO CAR TESTS

### Objectives and test procedure

For verification of the compatibility findings from barrier tests various car to car tests are conducted. In each case a small car is crashed against a big family saloon. The findings from car to car tests are compared with the results gained with barrier tests and examined in terms of conformity.

On the basis of compatibility results the following vehicle pairs are selected:

**Citroen Saxo** (the weakest of the small cars tested) against **Mercedes E** (a little bit aggressive big car)

**Citroen Saxo** against **BMW 520i** (a comparatively less aggressive big car)

**Ford Ka** (a comparatively compatible small car) against **Mercedes E**

**Ford Ka** against **BMW 520i**

**Ford Ka** against **Volvo S70** (a comparatively less aggressive big car).

Frontal impact tests are conducted with 50% offset overlapping for the small car. The impact speed of both cars is 50 km/h. Only in the crash Ford Ka against BMW 520i a speed of 55 km/h is reached due to a test facility fault. Dummy and luggage arrangements are identical with those of the barrier tests.

vehicle	Citroen Saxo		Ford KA		
V <sub>impact</sub> (km/h)	50,1	49,9	50,2	55,1	50,1
opponent	Mercedes E	BMW 520i	Mercedes E	BMW 520i	Volvo S70
head	4,3	3,9	3,2	2,8	3,0
neck	1,9	2,0	2,4	2,4	2,0
arms	4,5	4,3	4,5	3,5	3,8
thorax	3,2	3,1	2,8	2,5	2,6
abdomen	2,5	2,3	1,5	1,5	1,5
pelvis	5,0	5,0	4,0	2,7	4,0
legs	3,9	3,7	3,7	3,7	4,1

injury risk mark <sub>Mercedes</sub> > injury risk mark <sub>BMW/Volvo</sub>

**Figure 18. Injury risk marks for individual driver body parts of Citroen Saxo and Ford KA crashing against big vehicles**

### Findings

Figure 18. gives an overview of injury risk marks for individual body parts of the drivers of the Citroen Saxo and the Ford Ka. A comparison of the data shows:

- In the crash against the Mercedes E the injury risk for most body parts is slightly higher than for the crash against the other big cars. This confirms the findings from barrier crashes that the aggressiveness of the Mercedes is slightly higher.
- Also in car to car tests the injury risk in the Citroen Saxo is generally higher than in the Ford Ka. This is another confirmation of the findings of the barrier tests.

## SUMMARY AND CONCLUSION

The study had the objective to improve the existing frontal impact test procedure against the deformable barrier in order to not only generate findings on passenger protection but also on vehicle aggressiveness and therefore compatibility.

First compatibility is defined as a vehicle feature which is related both to self-protection performance and aggressiveness towards the other vehicle. The level of aggressiveness depends on the amount of energy and the force transmitted to the other party but also on whether such transmission is distributed over a broad surface or has only a local quality.

The current barrier does not supply this data and thus no information on compatibility. Moreover, this barrier's energy absorption is too low for bigger vehicles and penetration resistance is too low for vehicles with a highly non-homogeneous stiffness distribution which can have a negative effect on passenger protection results in terms of real-life accidents.

In order to avoid these disadvantages the barrier will be improved along the following lines:

- higher energy absorption capacity (about 2.5 times) by partition into several layers with gradually increasing stiffness
- higher penetration resistance through multi-layer feature
- force measuring device behind the barrier
- determination of dynamic pressure stiffness of the barrier

These measures provide the opportunity to gain the following additional crash testing information:

- force transmission to the other party (from the behind barrier force)
- energy transmission to the other party (from barrier deformation)
- horizontal and vertical front-end stiffness distribution (from homogeneity of barrier deformation).

A rating system is developed which considers both passenger protection and aggressiveness and thus allows for quantification of passenger protection as well as aggressiveness and compatibility from test results.

The testing of the new barrier and rating system is made within the framework of barrier tests with several small cars and big family saloons. Subsequent car to car tests confirm the compatibility findings from barrier tests.

It can be said that the new barrier is functioning very well and that its performance is by far superior to that of the today's European standard barrier. Energy absorption for all tested vehicles was adequate, there was no bottoming out of vehicle components on the barrier base.

The car to car tests confirm the practicability of the rating procedure. The hypotheses and standards used must however be elaborated and endorsed through additional tests.

## ACKNOWLEDGEMENTS

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# IMPLEMENTATION AND ASSESSMENT OF MEASURES FOR COMPATIBLE CRASH BEHAVIOR USING THE ALUMINUM VEHICLE AS AN EXAMPLE

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## ABSTRACT

The compatibility of passenger cars is mainly attributable to the parameters of mass, the shape of the contact surfaces and the rigidity of the vehicle's front end. Due to its low density, aluminum offers excellent conditions for compatible behavior in road traffic.

Using the Audi A8 as an example, a presentation is made of the design measures which have a positive impact on the distribution of kinetic energy on both the vehicles involved in a crash. Great importance is placed on structural and passenger simulations using FE and MBS programs during the concept phase of vehicle development.

In the meantime the compatible design of the vehicle's front end has been confirmed by test series performed by independent test centers. Findings show that the aluminum body is subject to highly regular deformation in an offset crash both with a vehicle of identical mass and with vehicles of lower mass. The aluminum body is also capable of absorbing a high proportion of the total energy produced by the two vehicles.

Finally, further test results are forming the basis for discussing how well the 40% offset crash at 40 mph (IIHS crash test) against a deformable barrier can simulate a real crash.

## INTRODUCTION

In addition to protection of the vehicle's own occupants, which has reached a high standard on account of the relevant legislation (e.g. FMVSS 208) and rating procedures (e.g. NCAP or IIHS), increasing significance is being attached to protection of the other party involved in an accident. In this respect the compatibility of the vehicles in head-on collisions as well as in side impact collisions must be considered.

The VW Group (Audi, SEAT, Skoda, Volkswagen) offers vehicles in a wide variety of mass and size categories for sale. There is accordingly much motivation to investigate the important topic of compatibility between different vehicles.

The difference in mass of the accident vehicles exerts a significant influence on compatibility in road traffic. For frontal impact, a simple consideration of momentum supports this as the velocity change of the heavier car will be less than that of the lighter car.

$$m_1 \cdot v_1 + m_2 \cdot v_2 = (m_1 + m_2) \cdot v_{\text{after}} .$$

The demands placed on the small light-weight vehicle by a heavier vehicle - especially in fully overlapped collisions - are superproportional. Even in the case of a lateral impact the high kinetic energy of colliding cars has a negative effect on the intrusions and thus directly on the potential for injury. A reduction of weight for large cars is therefore desirable for several reasons:

- Reduction of fuel consumption leading to greater environmentally friendliness.
- Improvement of the mass compatibility in road traffic.

As far back as the mid-eighties Audi began developing aluminum vehicles to reduce the effect of weight incompatibility of larger cars. Different studies showed that fatalities can increase for reduced weight cars when the reduction occurs through both mass and size reduction. But aluminum allows mass reduction to be achieved without changing size or reducing crashworthiness. The aluminum bodyshell was conceived anew and designed with the aid of extensive computer analysis, Figure 1.

By using FEA (Finite Element Analysis) and employing complex MBS models (Multi Body System) the vehicle structure and restraint systems were optimally coordinated. This paper sets out the advantages of the newly-developed Audi Aluminum Space Frame Concept (ASF) in real accident situations.

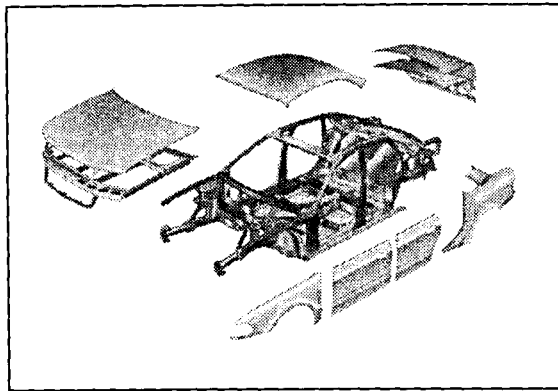


Figure 1. Audi A8 Aluminum Space Frame (ASF).

## Definition of Compatibility

When a single-vehicle accident occurs, injuries of the occupants depend on the collision mode, on the impact velocity, on the personal condition of the occupant and on the inherent safety of the car. Inherent safety is the ability to avoid injuries to its occupants, when a collision mode at a specific velocity occurs. This ability is measured by vehicle behavior and interpretation of the dummy kinematics and loads. The inherent safety of a car can also be called self protection or occupant protection.

In a car-to-car accident, collision modes, impact velocities, and the personal condition of driver can be observed in the same manner. But injury to the occupants does not only depend on the inherent safety of the car, but also on the structural behavior and mass of the **other** car. It is obvious that an accident between a heavy and a light car may be different from an accident between two light cars. An accident between a rigid and a yielding car might be different to an accident between two yielding cars. The distribution of the stiffness at the front of a vehicle might influence the interaction between the structures of the two colliding vehicles. In car-to-car accidents we therefore also study partner protection, the ability of the car to avoid injuries to other participants in the collision. Lack of partner protection is referred to as aggressivity. Vehicle aggressivity can be defined to be the number of fatalities/injuries in the vehicles struck by the subject vehicle divided by the number of subject vehicle registrations or by the number of crashes of the subject vehicle (aggressivity metric) /1/.

The goal of compatibility is to bring these two issues together

- to enhance partner protection

- without decreasing occupant protection

or to optimize occupant protection in such a manner that the overall crashworthiness performance of the vehicle is maximized.

Of great importance here is that the problems are faced both by the large, heavy car as well as by the smaller, lighter vehicle. If the smaller vehicle does not possess a stable passenger compartment, designed to receive the front structure forces of the opposing car, then there can be no compatible crash behavior in road traffic /2/.

## Data analysis

Figure 2 shows the situation as identified in the Volkswagen accident data base. This is a data base of 10160 passenger cars (53 % are not Volkswagen or Audi models). The accidents were collected in Germany.

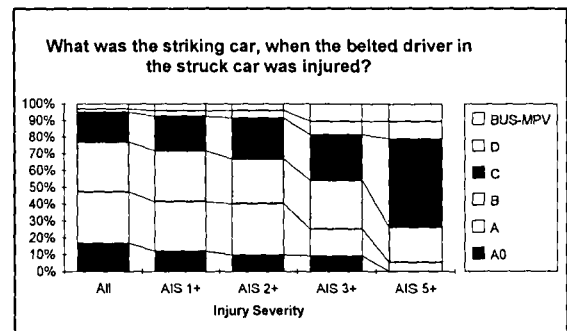


Figure 2. Distribution of the size-groups of the striking vehicles when a belted driver in a struck vehicle was injured.

The vehicles are divided in 6 groups: **A0** such as the VW Polo, Opel Corsa etc., **A** such as the VW Golf, Ford Escort, **B** such as the Audi A4, VW Passat, MB C-Class, **C** such as the Audi A6, BMW 5xx, MB E-Class, **D** such as the Audi A8, Volvo 7xx, MB S-Class and **Bus - MPV**, comprising minibuses like the VW Caravelle and similar products. Accidents between those types of vehicles were checked and it was registered what the striking car was when the belted driver of the struck car was injured. All collision modes are included. The data were checked for all belted drivers, injured and not injured, and for the different MAIS classes.

It can be observed that MAIS 5 and 6 occurs to a level of more than 90 % in crashes when a B-, C-, D-, or bus-type vehicle strikes another vehicle, although these groups are less than 55 % of the striking vehicles for all drivers.

In the United States the distribution is even more dramatic, as an analysis by the NHTSA working group on vehicle aggressivity and fleet compatibility shows /3/. Because of the high market share (approximately 50% of new registrations), the class of Light Trucks and Minivans are significantly represented in the number of fatal accidents. LTVs - which includes sport-utility vehicles, pickups and vans - are about twice as aggressive as passenger cars if the total number of fatalities in the opposing car is considered. A IIHS study /4/ even proves, that occupants of passenger cars are six times as likely to die when they collide with a large truck compared with another car.

This and other observations were the reason for Audi, Seat, Skoda and Volkswagen to form an internal expert group to study vehicle compatibility phenomena. Extensive analysis identified a number of parameters which significantly influence the compatibility behavior of a vehicle in a real accident situation.

#### **BASIS DESIGN CRITERIA FOR A COMPATIBLE VEHICLE BEHAVIOUR**

Crash incompatibility can be reduced. In order to achieve a coordinated crash behavior for two vehicles, three fundamental design guidelines - here described in outline - must be observed.

##### **Vehicle mass**

The difference in mass between the larger and the smaller vehicle must be minimized. With environmental friendliness in mind the target is to thus achieve a reduction of weight for large cars without changing size or reducing crashworthiness.

##### **Crush zone stiffness**

Structural factors include the frontal stiffness as determined from crash tests and engine location. The aim must be to make the stiffness of the vehicles compatible. This means that the passenger cell must be brought up to a sufficiently high impact level before it collapses and deforms the front below this impact level limit.

The stiffness should also be designed to produce a gradual impact level. This insures that the front structure absorbs at least a part of the kinetic energy in a side impact.

#### **Geometry and structural interaction**

The force of the front structure must be evenly distributed on the other vehicle. For this an extensive support for the longitudinal and engine forces - similar to a protective shield - is necessary. A deflection has a positive effect on the opposing car as it retains a part of the kinetic energy and must not be converted into deformation.

Geometrical factors also include the hood profile, sill and bumper height /5/.

#### **NUMERICAL EVALUATION OF CRASH COMPATIBILITY**

To evaluate the many parameters which must be considered in order to adhere to the above cited design guidelines a large number of costly crash tests are required. The ability of computer simulation to act as a substitute for actual car-to-car testing therefore has to be studied.

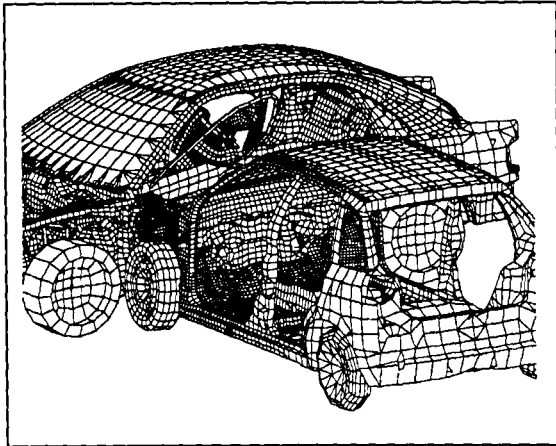
At the 15. ESV-Conference it was shown how computer simulation can be adopted in order to obtain a realistic analysis of these highly complex occurrences /6/. The great advantage of computer simulations is the possibility to conduct many optimizations with investigating only one parameter of the system. Calculation of variants and extensive optimization calculations can be conducted in this way, in order to determine the principal compatibility parameters and introduce improvements on vehicles.

Numerical evaluation of the complex occurrences in a car-to-car accident calls for the correct modeling of all relevant assemblies and part-systems /7/. By way of an example, an Audi A4/Seat Ibiza side-impact crash with regard to compatibility was analyzed with the finite element program PAMCRASH. The simulation model was built up as follows:

- 1) Modeling and validation of the Audi A4 side structure with the Euro-SID dummy, including the door trim and door padding, in a side crash according to EEVC conditions.
- 2) Checking the Seat Ibiza frontal crash model by means of a 55 kph „auto, motor und sport“ offset-test.

- 3) Combining the models and calculating structural behavior and EuroSID loadings in a car-to-car crash in which the Seat was driven at a right angle into the side of the Audi in accordance with EEVC experimental conditions.

Figure 3 shows one step of the crash analysis.



**Figure 3. Complete FE Model for Analysis of the Car-to-Car Compatibility Crash.**

In order to evaluate the loads on the occupants, a crash test was carried out with precisely the same peripheral conditions as in the numerical simulation. Because of the extensive validation already carried out, combining the various part-models presented no problems. Both the elapsed time and the maximum values in the calculation and the experiment coincided very well. The work showed that calculation of car-to-car accidents as a means of investigating compatibility is a tool capable of analyzing deformation behavior and the resulting loads on dummies in the preliminary development phase for various vehicle structures.

### THE DESIGN CONCEPT OF THE AUDI A8

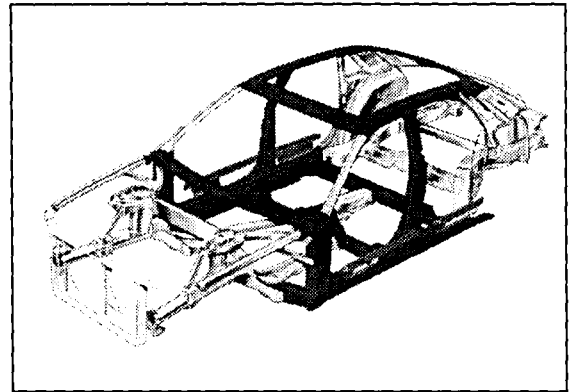
To really reduce the weight on an automobile dramatically you have to be consistent and start where the car is heaviest - on the bodyshell. The objective, after all, was to achieve a dramatic decrease in weight despite significant improvements in rigidity, the ability to absorb and take up impact energy, and driving characteristics under all conditions. Accordingly, particularly great significance was given to the crash simulation tests, the data obtained in this process being verified and confirmed in subsequent practical testing.

The technology which makes all this possible is the Audi Space Frame ASF. This development clearly

demonstrates the potential of aluminum for weight reduction without size reduction.

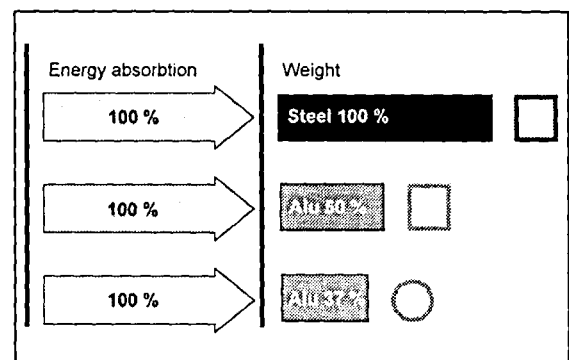
### Audi Space Frame ASF

ASF consists of extrusion-pressed aluminum profiles connected by vacuum-pressure-cast intersections and surrounding the entire passenger compartment, shown in Figure 4.



**Figure 4. The Audi Space Frame ASF Structure Concept of the Audi A8.**

The superior stability of the Space Frame results primarily from the intersected connections made of high-efficiency aluminum alloys and with the help of an optimized vacuum-casting procedure. In their thickness and shape, the intersections are tailored precisely to the specific loads varying from one part of the body to another. Figure 5 shows the fundamental advantage of aluminum used in the right design and configuration.

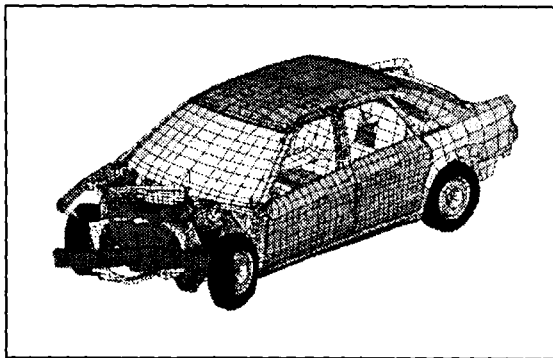


**Figure 5. Weight Comparison: ASF / Steel structural members during a crash.**

For comparing the weight and energy absorption of an unitary steel bodyshell with that of aluminum, you will see that the Audi Space Frame ASF is roughly 40% lighter despite its superior strength.

### **Frontal impact protection**

At the front area of the body shell the ASF structure is designed as a defined deformable front end. It possesses a side member system composed of aluminum extrusions and die cast nodes which is especially effective at converting impact energies into deformation. The side members are linked under the floor and along with the passenger cell form a stable composite which offers an excellent survival area. During the development of the front end structure the most up-to-date crash calculation procedures were employed, Figure 6.



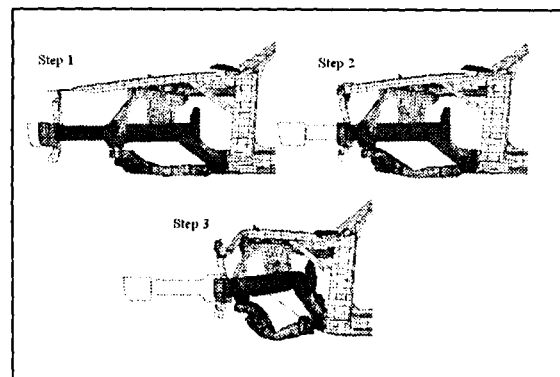
**Figure 6. FE-Analysis Offset Crash.**

The gradual deformation impact level of the side member system assures effective crash behavior at many different collision speeds. The front side member displays a high energy absorption capacity at an impact level of 80 kN. The aim was for an optimal realization of the following requirements in a design:

- high occupant protection,
- good compatibility for front and lateral collisions
- as well as a favorable insurance category rating.

A circular section achieves the favorable ratio of energy absorption to employed weight. The rear member section only undergoes deformation when the energy absorption of the front section has been concluded, Figure 7.

In a car-to-car accident the frontal structural impact is evenly distributed to the other vehicle by a solid bumper cross member and a stable front end (Figure 6).

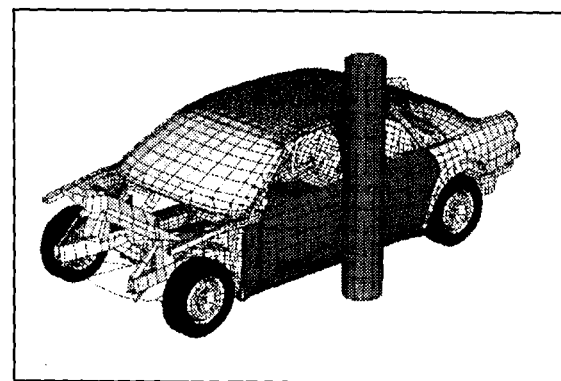


**Figure 7. Gradual side member deformation.**

### **Side impact protection**

The Audi Space Frame also provides an excellent survival capsule for the occupants in the case of a side impact. The high side structure rigidity is an important pre-condition for low passenger loads. The whole concept encompasses a multitude of individual measures that have been carefully coordinated via computer simulation. A major contribution is made by an interlocking structural brace which consists of the high-strength B pillar with a sheet metal shell and interior extrusions with wide sill steps, doors with flexural impact members and extensive structural overlaps. The rigid sills form just as much a part of the whole system as the large cross members in the seat area.

In addition to the crash test required by law Audi conducts further crash tests based on real accident situations. Exemplary is the lateral collision with a tree or pole as depicted in Figure 7.



**Figure 8. FE analysis of a pole impact**

Because of the high local loads the pole impact places particular demands on the body shell structure. The ASF's

ability to use the whole structure to dissipate the energy and thus to distribute the localized loads insures very good protection for the occupants even by a tree impact.

## COMPATIBILITY TESTS

### Side impact

The individual compatibility plays a important role for a car-to-car crash in the case of a side impact. The ASF safety cage is ideal for transferring high loads with low deformation.

#### Audi A8 - Audi A8 (self compatibility)

Impact velocity: 50 kph

Mass ratio 1.0

Test institute: Audi

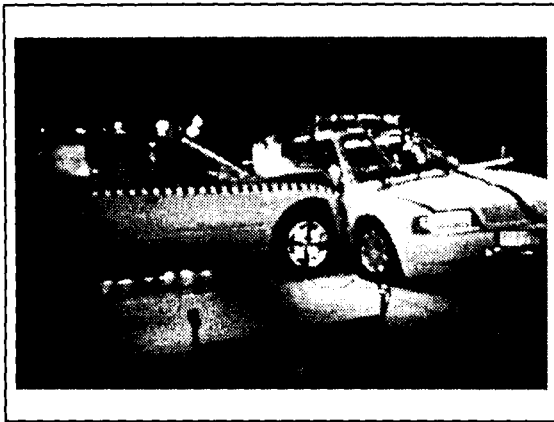


Figure 9. A8/A8 car-to-car lateral crash

The requirement for the self compatibility of vehicles heavier than 950 kg (mass of the deformable barrier) represents a tightening of requirements in comparison to the statutory side impact crash EG 96/27.

### Comparison of occupant loads

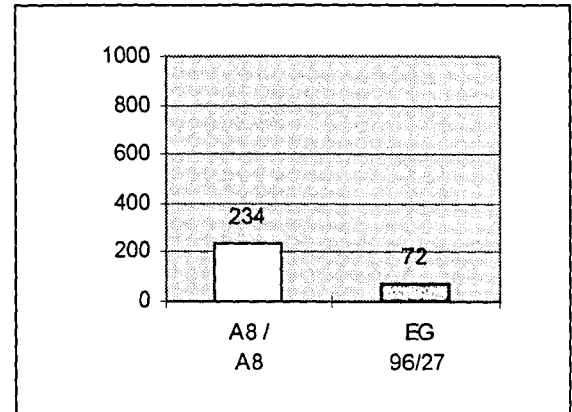


Figure 10. HIC self compatibility / EG 96/27.

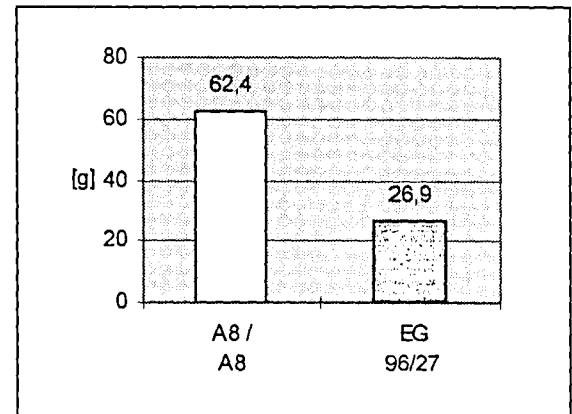


Figure 11. Head a(3ms) self compatibility/ EG96/27

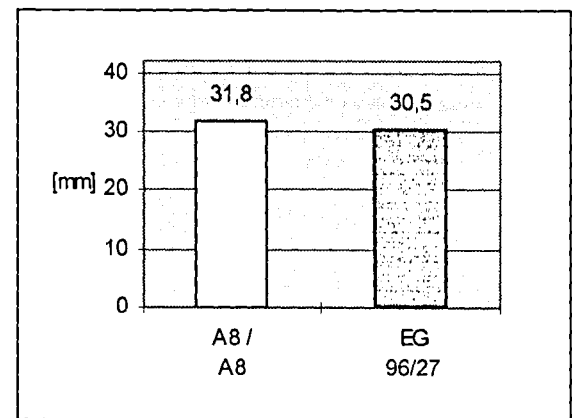


Figure 12. RDC self compatibility/ EG 96/27



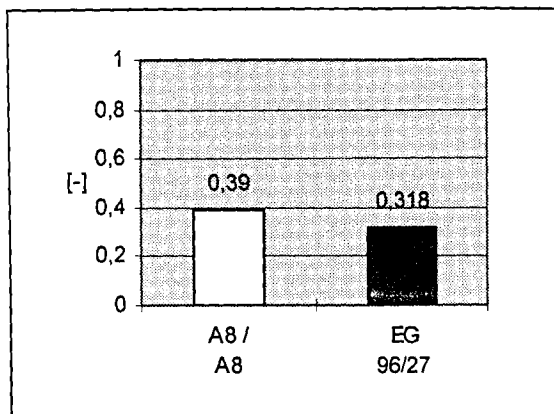


Figure 13. VC self compatibility/ EG 96/27

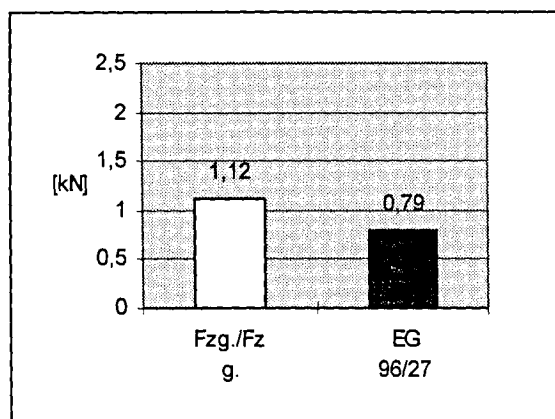


Figure 14. APF self compatibility/ EG 96/27

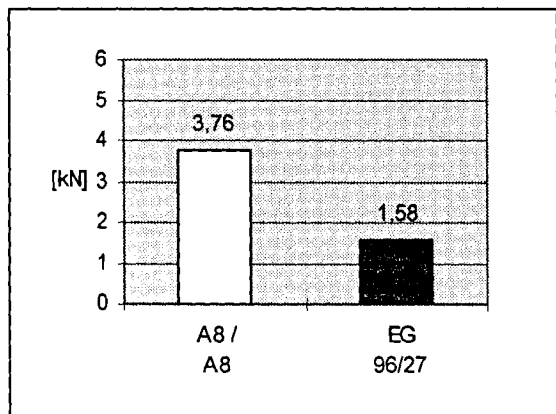


Figure 15. PSPF self compatibility/ EG 96/27

### Evaluation the side impact crash test

The solid aluminum bumper cross member in the front end of the colliding Audi A8 distributes the load across a

wide area into the side structure of the hit car and produces an even and homogenous deformation.

Despite this clearly higher demand made on the side structure of the ASF for individual compatibility in comparison to EG 96/27 the occupant protection values lie clearly below the statutory limits.

### **Frontal impact**

In car-to-car frontal crash tests with 50% overlapping the compatibility behavior of the Audi A8 was tested against different heavy collision partners.

#### Audi A8 - VW Polo

Speed: 50.0 kph ( $v_s$  100 kph)

Mass ratio: 1.48

Test institute: TÜV automotive commissioned by ams (Edition ams 18/95)



Figure 16. A8 / Polo car-to-car frontal crash

#### Audi A8 - Audi A3

Speed: 49.9 kph ( $v_s$  99.8 kph)

Mass ratio: 1.26

Test institute: TÜV automotive commissioned by ams (Edition ams 6/97)



Figure 17. A8 / A3 car-to-car frontal crash

### Audi A8 - Audi A8

Speed: 56.5 kph ( $v_s$  113 kph)  
 Mass ratio: 1.0  
 Test institute: VW-WOB

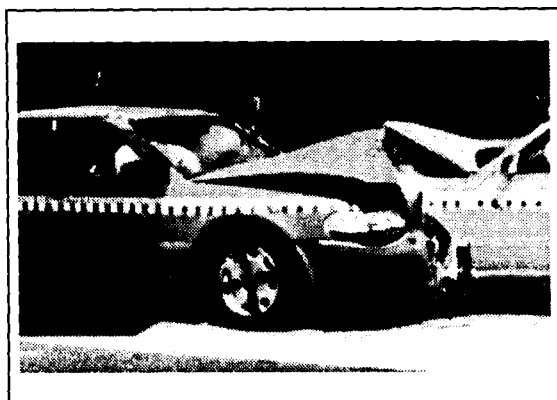


Figure 18. A8 / A8 car-to-car frontal crash

### Audi A8 - same class (2157 kg)

Speed: 56.5 kph ( $v_s$  113 kph)  
 Mass ratio: 0.92  
 Test institute: VW-WOB

### Audi A8 - same class (2560 kg)

speed: 54.7 kph ( $v_s$  109.4 kph)  
 Mass ratio: 0.78  
 Test institute: TÜV automotive commissioned by AUDI

### Comparison of occupant loads

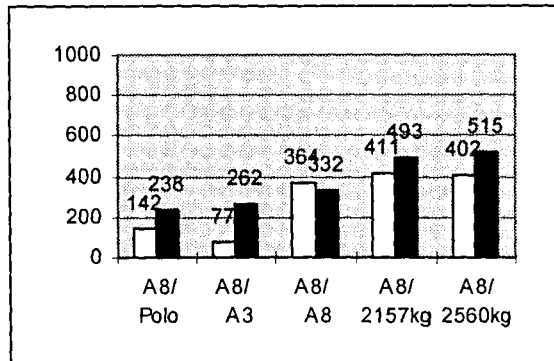


Figure 19. HIC: A8 / Partner frontal crash

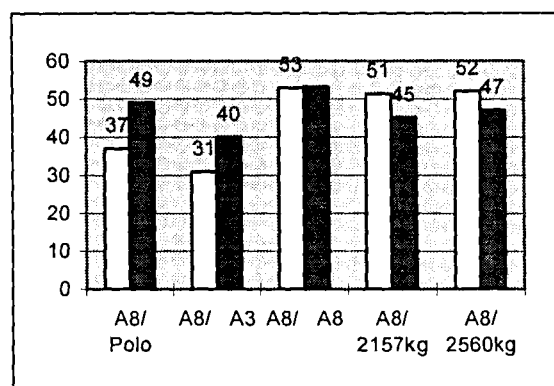


Figure 20. Chest [g]: A8 / Partner frontal crash

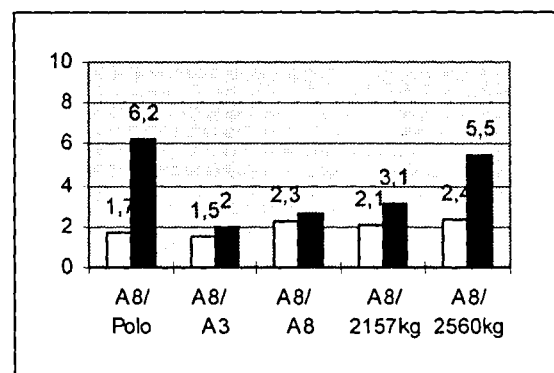


Figure 21. Femur [kN]: A8 / Partner frontal crash

Head and chest loads in both crash partners display similar load levels. Because of the vehicle kinematics caused by the difference in mass, the Audi A8 vehicle delays in collisions with lighter crash partners are lower. This is reflected in the lower occupant loads in the Audi A8. The relatively high knee loads in the Polo are caused by the higher vehicle intrusions; the hard local impinging of the instrument panel on the 2560 kg vehicle is the cause for the high value recorded for the right knee (left knee 2.5 kN).

The test results show that not only does the Audi A8 offer a very high level of protection for the Audi occupants but that relatively balanced occupant loads are recorded in the crash partner vehicles. The frontal impact protection measures introduced in the front end show quite impressively that the Audi A8 is effective in guaranteeing partner protection.

### Comparison of the vehicle structure deformation

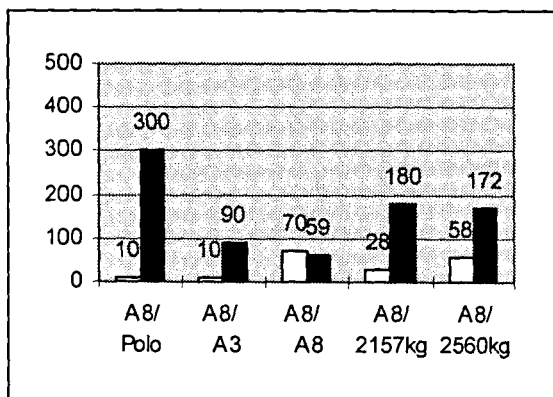


Figure 22. Footwell intrusion in [mm] A8 / partner frontal crash

The very low footwell intrusions in the Audi A8 show the effectiveness of the rigid 'security cage' of the ASF vehicle structure even in cases of serious accident collisions.

### Evaluation of the frontal crash tests

On the basis of the low mass and the gradual deformation behavior in the front end the Audi A8 provides sufficient deformation path in the tests in order to convert the kinetic energy so that the occupant load in both vehicles can be predicted to reach a non-critical level.

Overall the tests show that the Audi A8 exhibits a distinct compatibility crash behavior.

## **How well simulate the 40% offset crash at 40 mph (IIHS/Euro-NCAP) against a deformable barrier a real crash?**

The results of a IIHS study /8/ suggest that a 40 percent offset crash into a deformable barrier at 64 kph represents a real-world crash severity below which about 75 percent of all MAIS 3 or greater injuries and roughly half of all fatal injuries to passenger car occupants in frontal offset crashes occur in the United States. The frontal crash tests conducted above with 50% overlapping were compared to the offset crash IIHS in the following.

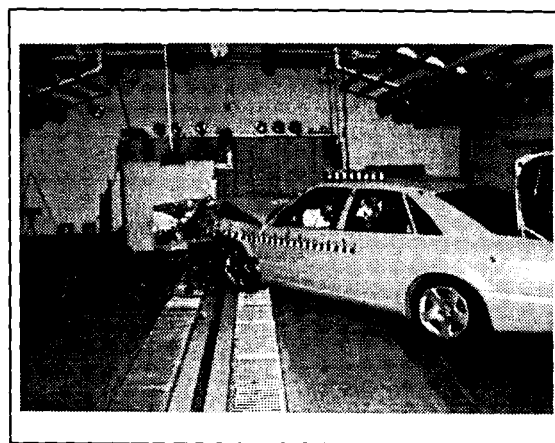


Figure 23. A8 Offset IIHS

### Comparison of the occupant load

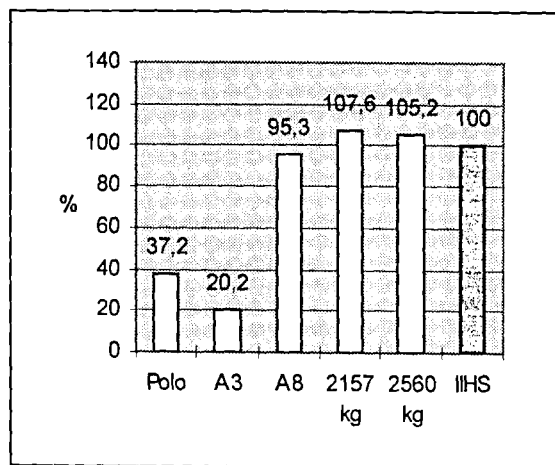


Figure 24. HIC: A8 against partner

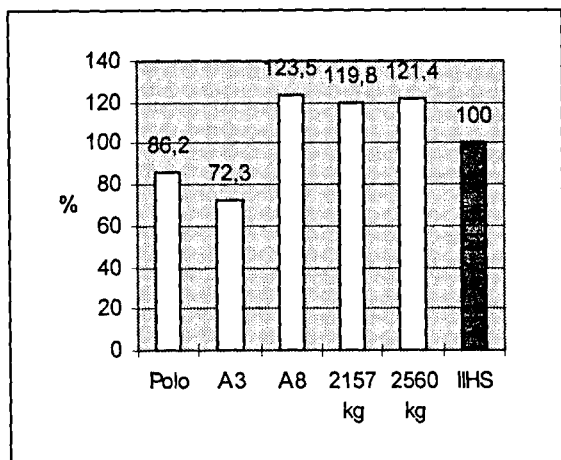


Figure 25. Chest acceleration: A8 against partner

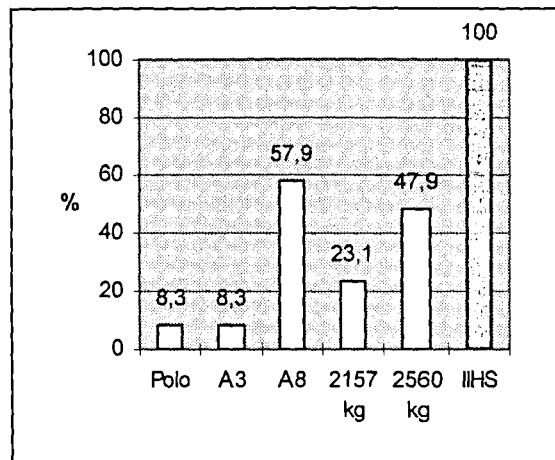


Figure 27. Footwell intrusions: A8 against partner

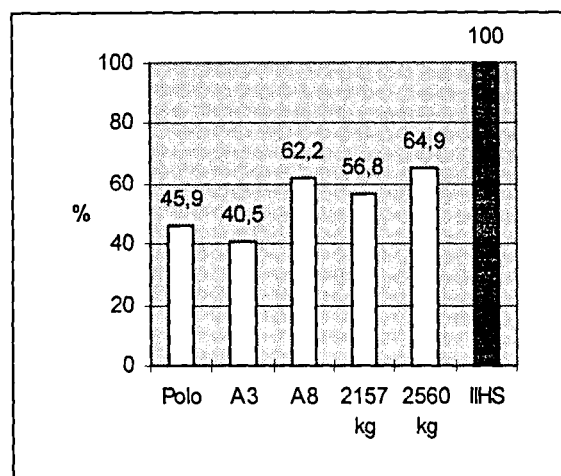


Figure 26. Femur load: A8 against partner

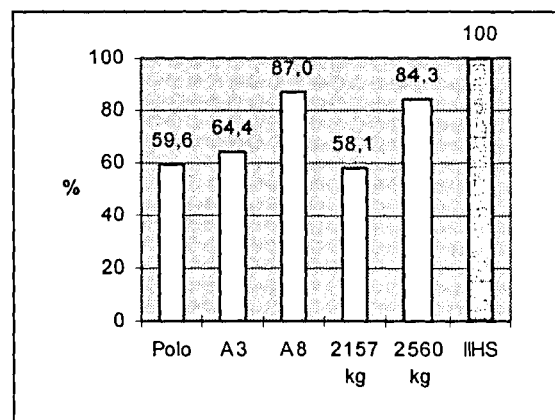


Figure 28. Front end deformation: A8 against partner

The HIC in the offset crash IIHS is of a similar level as the car-to-car crash tests. The chest loads are lower, the thigh forces tend to be higher.

### Comparison of the vehicle structure deformations

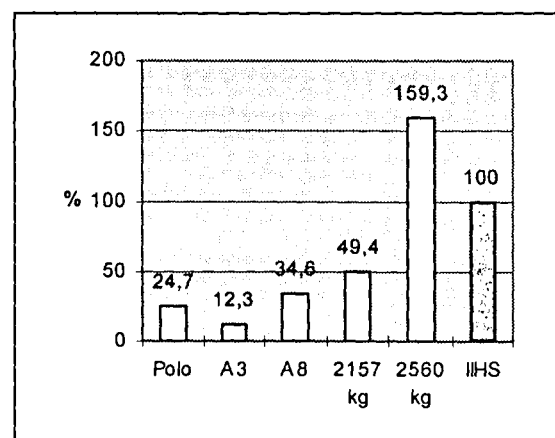


Figure 29. Side structure deformation; A8 against partner

## **Evaluation**

Both the footwell intrusions of the vehicle cell as well as the front end deformations in the offset crash IIHS are higher than in the car-to-car crash tests.

The deflection effect in the car-to-car crash is not considered in the offset crash IIHS. At this impact speed the Audi A8 deforms the barrier completely and hits the bare wall.

## **Results**

It is evident that the IIHS offset crash deforms the Audi Space Frame differently in comparison to the car-to-car crash tests. A higher occupant load was not ascertained in the offset crash IIHS.

The footwell intrusions, which occur at this level in the fully overlapped frontal crash as 35 mph against a bare wall, mean that an impact velocity of 64 kph for vehicles in the C class and above (luxury cars) and for LTV's should be discussed to achieve an additional development potential for compatible behavior in real accident situations.

## **CONCLUSION**

The work presented here shows that aggressivity/compatibility is not just a LTV vs. passenger car issue but also applicable between the various size and weight classes of passenger cars. An overall view must be equally taken incorporating the front as well as the side impact. In this respect computer simulations will take on an increasingly important role. The applicability of current methods has already been shown.

In addition to a mass reduction for larger cars, for example, by utilizing light-weight metals such as aluminum, detail solutions are those which ensure that vehicles behave in a compatible manner. For example, it is essential for a strong cross-structure to be retained at the front - like a protective shield - in order to prevent aggressive behavior and distribute the loads on the other car. Similarly, a coordinated deformation characteristic in the front structure is plausible, in order to ensure a high level of partner protection, but also good protection for vehicle occupants in a single-car accident. Precisely these in-depth investigations make computer simulation essential, since it permits each individual parameter to be investigated and optimized separately.

Tests conducted by independent institutes have shown that the Audi A8 with its newly developed aluminum ASF technology displays a compatible behavior in car-to-car accidents. The occupant load and the structural deformation of both vehicles lie within acceptable limits

both against small, light-weight vehicles as well as against larger, heavier vehicles.

The IIHS or Euro-NCAP offset crash with 64 kph against a deformable barrier tends to be used to analysis real crashes; however, it cannot replace using car-to-car crashes. It has been shown that the load values for the vehicle occupants admittedly lie in the area of a crash with approximately a closing speed of 110 kph against a vehicle of identical mass, but that there is a different deformation picture with higher intrusions in the footwell areas for big cars like the Audi A8. A reason is the non-existing deflection of the vehicle from the deformation element. An increase in the impact velocity against the barrier of over 64 kph does not achieve the goal. A unrequired stiffening of the front end would be the result.

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# THE COMPATIBILITY OF MINI CARS IN TRAFFIC ACCIDENTS

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Paper Number 98-S3-O-08

## ABSTRACT

The compatibility problems of the mini car in car-to-car frontal collision and car-pedestrian accident are discussed using accident data and computer simulations.

In our analysis of the accident data in Japan, the number of fatalities was investigated using the vehicle masses and classes. It was found that the cars with identical mass are most compatible since the injuries per accident are minimal and injury risks to the driver in both cars are the same. The analysis of the car class indicated that the mini car and the sports utility vehicle are the most incompatible car types, with low and high aggressivity, respectively.

Our accident analysis in the present study shows that the safety of mini cars is the key point in achieving the compatibility in Japan. Computer simulations using MADYMO were carried out of crashes of mini car into a rigid wall and into a large car. It was found that either stiffening mini car with an optimized restraint system or modifying the large car with additional crush space can reduce the injury risk to the driver in the mini car.

The analysis of car-pedestrian accidents in Japan shows that the mini car has higher aggressivity in relation to the pedestrian than other bonnet-type cars. Computer simulation revealed that the head velocity of the pedestrian at impact is high since the pedestrian head contacts the body of the mini car in the early phase.

## INTRODUCTION

In vehicle-to-vehicle collisions, the protection of all occupants in the subject and other vehicle should be considered. This compatibility problem was first discussed in connection with the Experimental Safety Vehicle (ESV) in 1970 and has not been solved yet. EC/EEVC has a leading responsibility for vehicle compatibility, which is one of the harmonized research activities of ESV [NHTSA 1996]. In the United States, the National Highway Traffic Safety Administration (NHTSA) has started a research program on this subject [Hollowell and Gabler 1996]. However, in Japan, there seems to have been little research on vehicle compatibility in the past decade. One reason is that it has been difficult to obtain accident data in Japan.

Thus, the Institute for Traffic Accident Research and Data Analysis (ITARDA), established in 1992, provides some accident data.

Compatibility means that passenger vehicles of disparate size provide an equal level of occupant protection in car-to-car collisions [NHTSA 1996]. The field data show there are many vehicles which are incompatible with other vehicles. This incompatibility is induced by the difference in the mass, stiffness, geometry and structure of both vehicles [Buzeman 1997]. An incompatible vehicle induces high injury risks for the occupants in the other vehicle, which can be defined as aggressivity. The influences of mass, stiffness and geometry are combined and have aggressivity to other cars.

One purpose of the present study is to identify the compatibility problems of car-to-car and car-to-pedestrian collisions in Japan based on the accident data using vehicle masses and classes. The compatibility problem should be examined for each country because the traffic environment differs in each country in terms of vehicle size, population, velocity, travel distance and the road environment.

In car-to-car collisions, the injury risk to the occupants in a mini car is high due to high delta-V and large intrusion based on its small mass and size. To achieve the compatibility of this type of a car, a low mass vehicle (LMV) with a mass of 600-650 kg and length of 2.5-3.0 m was proposed [Waltz et al. 1991; Kaeser et al. 1992, 1995; Frei 1997]. The front structure of a LMV is designed to be stiff in order to reduce the intrusion into the passenger compartment. As the acceleration of a LMV becomes high due to the stiff structure, it needs a specially designed restraint system to ensure the occupant's safety. Optimum restraint system was analyzed using the crash victim simulation program MADYMO [Kaeser et al. 1995; Muser et al. 1996]. However, this analysis was conducted only for a crash with a deformable barrier. The analysis of the compatibility in a car-to-car collision is necessary to show the injury-reducing effect of high stiffness and the optimized restraint system of a LMV.

The safety of the occupant of a small car in a car-to-car frontal collision has been investigated in many studies by a mathematical model. The force-deformation characteristics of both cars were examined in order to decrease the acceleration and deformation of the small car

using a simple spring-mass model [Ventre 1972, 1973; Appel et al. 1994; Tarrière 1994]. Finite element analyses of a car-to-car frontal collision were also conducted to describe the interaction of components of both cars [Maurer et al. 1996; Tarrière 1996]. These analyses of car-to-car collisions focused mainly on the car characteristics, and the model consists only of a vehicle without an occupant. Therefore, the influence of the car stiffness on the injury risk of the occupants by a combination of acceleration and intrusion in car-to-car frontal collision is not clear.

The compatibility of a mini car in a collision with a large car has to be achieved without increasing the injury risk to the driver of the mini car in a single-car crash. In the current study, the crash of a mini car into a rigid wall with full overlap, and the collision with a large car with a 50% overlap are simulated using MADYMO. The influences of front stiffness and the restraint systems of the mini car on the injury risk to the driver are studied to achieve the compatibility of the mini car in frontal collisions.

Since mini cars are mainly used in the city, car-pedestrian accidents are of great importance. The front geometry of the vehicle affects the pedestrian injury risk [Ishikawa et al. 1991]. Therefore the injury risk to the pedestrian struck by a mini car was examined by the analysis of the accident data and also computer simulation using MADYMO.

## METHODOLOGY

### Accident Analysis of Mini Car Crash

**Distribution of Fatalities by Accident Type** - The distribution of fatalities can be expressed for all types of accidents by fatalities related to the subject car [Appel 1996]. The fatalities can be distinguished as internal and external in relation to the car. Fatalities of the subject car in car-to-car collisions and in single car accidents are classified as internal fatalities, while those of other cars, motorcyclists, cyclists and pedestrians are classified as external fatalities. Fatalities in all types of accidents are estimated by the number of internal and external fatalities per registrations of the subject car.

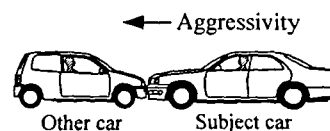
**Compatibility in Car-to-Car Frontal Collision** - The goal of vehicle compatibility in car-to-car frontal collisions is to minimize the number of fatalities while the injury rates of the occupants in each car remain the same. Thus, in the current study to estimate compatibility in a car-to-car frontal collision, one method is employed to determine the total number of fatalities in both cars per accident when comparing the ratio of the fatalities occurring in each car.

To estimate the aggressivity in car-to-car frontal collisions, the following methods can be used:

1. (Number of fatalities in other cars) / (Number of fatalities in subject cars)
2. Percentage of fatalities in other cars
3. Number of fatalities in other cars per million subject car registrations

Methods 1 and 3 were suggested by Hollowell et al. [1996]. Using method 1, the aggressivity of a car without influence of human factors can be described. If the crash velocity of the subject car is high, the injury risk to the occupants in other cars as well as in the subject car is high. Thus, the influence of crash velocity on the aggressivity estimated by method 1 will be small. On the other hand, the aggressivity of the car including influence of crash velocity is estimated when the injury rate of the driver in the other cars is used in method 2. If the crash velocity of the subject car is high, the aggressivity obtained by method 2 will be higher because the number of fatalities in the other cars will increase. The aggressivity estimated by method 3 includes the effects of travel distances, vehicle velocities and accident rates, reflecting how they are used (Table 1.).

Table 1.  
Effect of Crash Velocity and Accident Rate on Aggressivity  
Using Each Method



Method	Crash Velocity	Accident Rate
1	X	X
2	O	X
3	O	O

O = large effect      X = small effect

The method of examining aggressivity depends on the problem under investigation. For example, car manufacturers can use method 1 to estimate aggressivity of cars because this method is related to the car itself. Method 2, which includes the velocity effect, is usable in studies dealing with driver behaviors. Method 3 expresses the aggressivity of each registered car, so it can be used when insurance problems are investigated. In the current study, only method 1 is used to discuss the aggressivity of the car itself.

The law enforcement accident data for the four years from 1992 to 1995 were used. The analysis is conducted only for cars with a model year of 1988 or later. In the current research, cars are categorized in eight classes: mini, sedan A, sedan B, sedan C, sports & specialty, wagon, IBOX and Sports Utility Vehicle (SUV). Only injuries to drivers are examined to simplify the analysis.



## Computer Simulation of Mini Car Crash

**Car Model** - The car model used in the computer simulations is based on a currently produced mini car. Figures 1 and 2 present a model of a car used to simulate crashes into a rigid wall and large car. The mass of the mini car is 700 kg, which is slightly larger than the average mini car (639 kg; Mizuno et al. 1997), and the mass of the large car is 1400 kg.

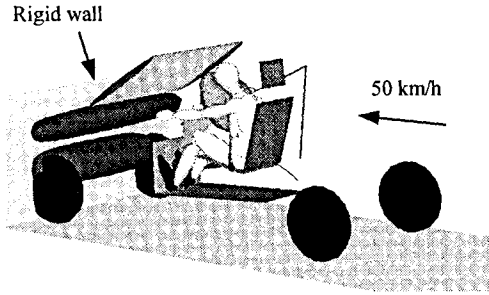


Figure 1. Simulation model of a mini car in a frontal crash into a rigid wall.

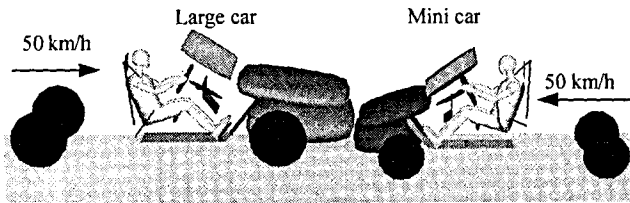


Figure 2. Simulation model for a frontal collision between a mini car and a large car with a 50% overlap for mini car.

Car front structures are represented by the ellipsoids. In the current model, the force-deformation characteristics of the mini and large cars are approximated by a straight line. The regression of the stiffness of the car ( $k$ ) is expressed using car mass ( $m$ ) as follows [Ishikawa 1990]:

$$k = 78m^{1/3} \text{ (kN/m)}. \quad (1.)$$

Using Eq. (1), the stiffness of the current mini car (700 kg) is evaluated as 693 kN/m. The stiffness of the mini car is changed from 500 to 1000 kN/m in order to examine the effect of the stiffness in crashes into a rigid wall and into a large car. The stiffness of the large car (1400 kg) is calculated as 872 kN/m by Eq. (1), which is used in the simulation of a car-to-car collision.

In an offset crash, the damage profile of the car is classified into direct damage and induced damage. Due to the induced damage, the stiffness of the car in the offset crash increases by 30% per width of the car [Ishikawa 1995]. Thus, the front stiffness of the car in an offset

collision is estimated as:

$$k_{\text{offset}} = 1.3k \times (\text{overlap ratio}) \quad (2.)$$

where  $k_{\text{offset}}$  is the stiffness of the car in the offset crash and  $k$  is that in the full overlap crash. In car-to-car collisions, the forces acting on both cars have the same magnitude but a different direction. The deformation of each car is calculated using force-deformation characteristics according to this force.

According to Matsumoto et al. [1990], the intrusion of the firewall ( $x_{\text{firewall}}$ ) can be approximated as:

$$x_{\text{firewall}} = 0.75(x - x_0) \quad (3.)$$

where  $x$  is the deformation of the car and  $x_0$  is the car deformation when the engine contacts the firewall. The deformation  $x_0$  of the mini car is smaller than that of the large car due to its small size. In the current model,  $x_0$  is estimated as 0.175 m for a mini car and 0.350 m for a large car. Based on the experimental results (Figure 3.), the longitudinal displacement of the steering column ( $x_{\text{steering}}$ ) can be expressed by the intrusion of the firewall ( $x_{\text{firewall}}$ ) as:

$$x_{\text{steering}} = 0.772(x_{\text{firewall}} - 0.0566). \quad (4.)$$

In the model, the movements of the firewall and steering column are simulated as the displacement of translational joints based on Eqs (3) and (4). To express the intrusion of the firewall, the toe pan is designed to rotate first, and upon becoming perpendicular moves in the driver's direction.

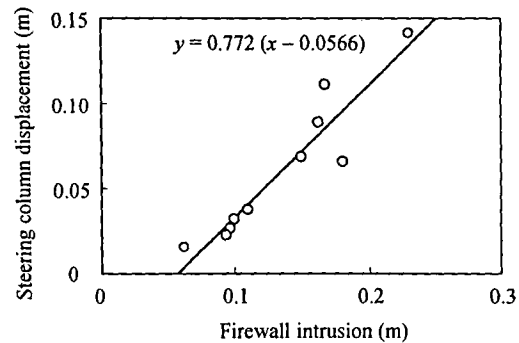


Figure 3. Relation between the firewall intrusion and longitudinal displacement of the steering column.

The HYBRID III database from MADYMO is used for the driver. The seat belt (10% webbing) and airbag (35I) is used for the basic restraint system for drivers in mini and large cars. This combination of restraint systems is commonly used in the current cars.

### Mini Car Crashes into Rigid Wall and Large Car -

The fatalities of the driver in single-car and head-on collisions account for a large portion of the driver fatalities in mini car accidents. Crashes into a rigid wall and car-to-car frontal offset collisions are representative of many cases of single-car and head-on collisions. In the present study, the simulations of the crash of the mini car into a rigid wall and the crash between mini and large cars with 50% overlap for the mini car were carried out.

According to the current regulation in Japan, the crash velocity of a mini car into a rigid wall is 40 km/h. In this simulation the crash velocity is put at 50 km/h, similar to the crash regulation of other types of cars. In the simulation of the car-to-car frontal collision, the crash velocity of each car is 50 km/h. The influence of the stiffness of the mini car on the injury risks to the driver in crashes into a rigid wall or a large car are examined. The injury criteria of the driver from the simulations are compared with threshold levels (HIC 1000, chest acceleration 60 g, chest deflection 0.075 m, femur force 10 kN).

**Effect of Restraint Systems** - The effects of restraint systems, including a seat belt force limiter, pretensioner (4 kN, 0.15 m), energy absorbing (EA) steering system (4 kN, 0.15 m), knee bolster and their combination, on the injury risk of the driver in a mini car are examined. The stiffness of the mini car is 1000 kN/m, which is larger than that of current mini cars to reduce the intrusion into the passenger compartment in a crash. The results are compared with those when a basic restraint system (airbag and seat belt) is used. The injury risks to the driver in the mini car in crashes into a rigid wall or a large car are studied when each restraint system or its combination is used with the basic restraint system.

**Additional Crush Space of Large Car** - When a large car has additional crush space designed for colliding with a mini car, the injury risk to the driver in the mini car may decrease. Tarrière et al. [1994] proposed a maximum force level 200 kN of a heavy car for compatibility with small car. Thus, in the present study, the additional crush length ( $c$ ) of 0 to 0.4 m with a force level of 200 kN is simulated (Figure 4.) without changing the front length of the large car.

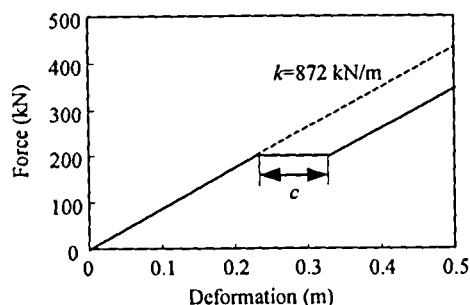


Figure 4. Additional crush space of a large car.

### Car-Pedestrian Accidents

**Accident Analysis** - The compatibility in car-pedestrian accidents involves the mass, stiffness and geometry of the car. The car mass has little effect on a pedestrian injury because even the lightest car is much heavier than the pedestrian. The simulation demonstrated that the geometry of the car has a larger effect on the pedestrian injury than the stiffness [Ishikawa et al. 1991]. Thus, in order to clarify the influence of the geometry of the car, pedestrian accident data were examined in terms of car class since the cars have a similar geometry in the same car class.

Pedestrian accidents where the pedestrian was struck by the front of the vehicle were selected. To exclude the influence of impact speed of the vehicle, the accident data were used in which the velocity recognized to be dangerous was below 40 km/h. The velocity recognized to be dangerous is one of the items included among the accident data, which is defined as the velocity at the moment the driver perceives the danger of striking a pedestrian. It indicates the velocity before the driver brakes or steers to avoid the accident, and is compiled mainly from drivers' testimony. The distribution of the injuries according to the body region of the pedestrian were examined from accidents with fatal or severe injury to the pedestrian.

**Simulation of Car-Pedestrian Accidents** - Computer simulations using MADYMO were performed to examine the influence of vehicle geometry on the injury risk to the pedestrian (Figure 5.). Elderly people are frequently involved and injured in car-pedestrian accidents [Ishikawa et al. 1991]. Thus, the elder pedestrian model was made based on the average Japanese male aged 60 to 69, whose height and weight is 161.3 cm and 59 kg, respectively. The geometry, mass, moment of the inertia and center of the gravity of segments of this pedestrian model are generated by the GEBOD (Generator of Body Data). The joint characteristics and the stiffness of the ellipsoid of the pedestrian are based on the biomechanical data [Ishikawa et al. 1993; Yang 1998].

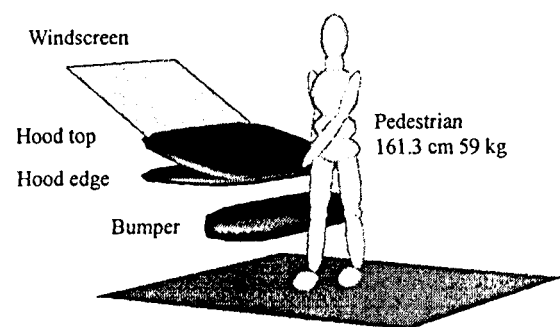


Figure 5. Pedestrian and vehicle model.

Three vehicle models representing mini car, sedan B and IBOX were made to evaluate the injury risk to the pedestrian for each car. In examining the influences of vehicle shape on the pedestrian struck by a car, the model was designed so that the same part of the vehicle would have the same force-deformation characteristics in three vehicles. The crash velocity of the car is 40 km/h.

In order to estimate the injury risk to the pedestrian, the injury parameters [i.e., the HIC, chest, pelvis and femur accelerations (3 ms)] of the pedestrian in crash were evaluated for three car models. The results of the simulation were compared with those of statistical analysis of pedestrian accidents.

## RESULTS

### Accident Analysis of Mini Car Crash

**Distribution of Fatalities by Accident Type** - From accident data in Japan, the distribution of fatalities was calculated. This distribution was examined by the number of fatalities internal and external to the subject car in various types of accidents. Figure 6 shows the number of fatalities in relation to the subject car per million registrations.

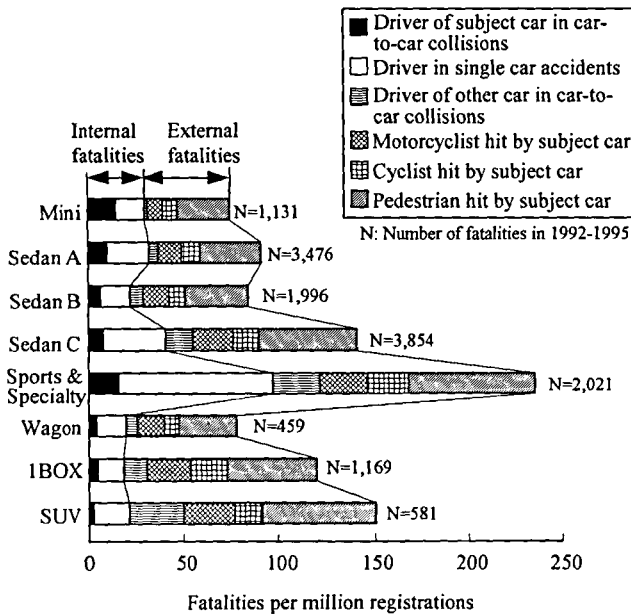


Figure 6. Internal and external fatalities of various subject cars for different types of accidents.

Sports & specialty, SUV, IBOX and sedan C vehicles cause more external-type fatalities than any other type vehicles. SUV and sports & specialty car, in particular, cause the most fatalities in the other car in car-to-car collisions. Cyclists sustain more fatalities when struck by sports & specialty car and IBOX vehicle, while more

pedestrians die from accidents involving sports & specialty car and SUV.

From the analysis of distributions of fatalities, it is found that the total number of fatalities of mini car is lowest, so this car type could be considered as most compatible vehicle. But this conclusion cannot be drawn because the mini cars are used for short-distance travel at a relatively low velocity [ITARDA 1996a] and also the frequency of driver internal fatalities in car-to-car collision is high. It is also necessary in the analysis of the compatibility to exclude the influence of factors which are not related to the car itself, such as driver behavior, car velocity and accident rate.

The number of fatalities in single car accidents involving sports & specialty cars is especially large, reflecting their higher crash velocity and accident rate compared to any other car classes. As a result, the number of fatalities involving sports & specialty cars is large for all types of accidents.

**Compatibility in Car-to-Car Frontal Collision** - Car mass is one of the most significant factors affecting driver injury in car-to-car collisions. It is well known that the fatality rate of the driver decreases with car mass. Evans [1993] found that the ratio of the injury rate in a lighter car to that in a heavier one may be expressed by the power ratio of the car mass of the heavier car to that of the lighter car. In the present study, the individual injury rate is expressed by average car mass ratio.

According to Joksch [1993], the injury rate  $R$  (%) can be expressed by delta-V ( $\Delta v$ ) as:

$$R = |\Delta v / \alpha|^k \quad (5.)$$

where  $\alpha$  and  $k$  are parameters obtained by curve fitting. For many head-on collisions, delta-V is approximated for a central collision. Assuming the restitution coefficient is zero, the delta-V can be expressed using the average mass ratio as:

$$\Delta v_1 = \frac{m_2}{m_1 + m_2} v_c \quad (6.)$$

where  $\Delta v_1$  is the delta-V of car 1,  $v_c$  is a closing speed, and  $m_1$  and  $m_2$  is the mass of car 1 and 2, respectively. Substituting Eq. (6) for (5), the injury rate of driver 1,  $R_1$ , is given by

$$R_1 = \left| \frac{m_2}{m_1 + m_2} \frac{v_c}{\alpha} \right|^k = a \left( \frac{m_2}{m_1 + m_2} \right)^k \quad (7.)$$

where  $a = |v_c / \alpha|^k$ . When Eq. (7) is applied to a real

accident, the probability of serious and fatal injury to the driver of car 1 can be calculated as shown in Figure 7. The parameters  $k$  and  $a$  are calculated for seat belt wearing and injury severity as shown in Table 2. Based on this method [Mizuno et al. 1997], the parameter  $k$  is obtained as 2.64 for belted drivers sustaining fatal and serious injury. This value is almost the same as the 2.62 shown by Evans [1994]. However, he calculated the injury ratio of belted car drivers in heavier cars to those in the lighter cars, and considered all directions of impact.

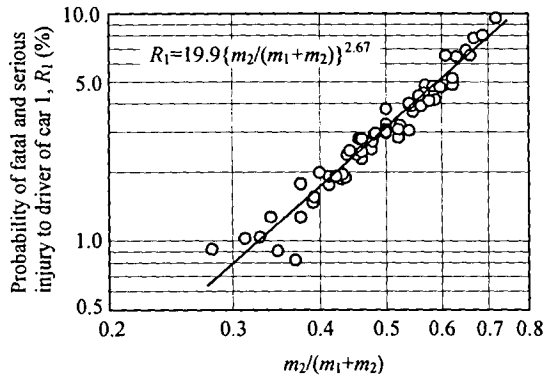


Figure 7. Average mass ratio and probability of driver injury in car 1 (Belted and unbelted driver).

Table 2.  
Parameter  $k$  and  $a$

Injury severity	Seat belt	$k$	$a$
Fatal and serious	Belted	2.64	13.9
	Unbelted	2.49	33.4
Fatal, serious, and minor	Belted	1.08	107.8
	Unbelted	0.955	123.5

The percentage of driver injuries in the subject car plus that in the other car corresponds to the driver fatalities per accident. From Eq. (7), we obtain

$$R_1 + R_2 = \frac{m_1^k + m_2^k}{(m_1 + m_2)^k} a. \quad (8.)$$

$R_1 + R_2$  has a minimum as  $2^{1-k} a$  ( $k > 1$ ) when  $m_1 = m_2$ . Thus, cars with equal masses are most compatible in a collision since the injuries per accident are minimal and the injury rate is equal for both cars.

The percentage of driver fatalities in the subject and other car is shown in Figure 8. As the mass of the subject car increases, the fatality rate of the driver in the subject car decreases; on the other hand, that of the driver in the other

car increases. The sum of the percentage of driver fatalities in the subject and the other car indicates the number of driver fatalities per accident where the subject cars are involved. When the car mass is 1150 kg, the number of fatalities per accident takes the minimum value, while the fatality rate of the subject car and that of the other car are almost the same. Then, the car with a mass of 1150 kg is considered most compatible in the current car population in Japan. The compatible car mass of 1150 kg is almost the same as the average mass of passenger cars in Japan, that is 1131 kg [Mizuno et al. 1997]. This is because there is a high possibility that the subject car with mass close to the average will crash into the other car with a small mass difference from the subject car.

When the mass of the subject car is in the range of  $750 \text{ kg} < m < 1350 \text{ kg}$ , the number of fatalities per accident is small. However, when the subject car mass is less than 750 kg or greater than 1350 kg, the number of driver fatalities per accident increases. Thus, in order to decrease the total number of fatalities, it is necessary to design the lighter car so as to keep in mind the safety of the drivers in the subject cars, and to design the heavier car while keeping in mind the safety of the drivers in the other cars.

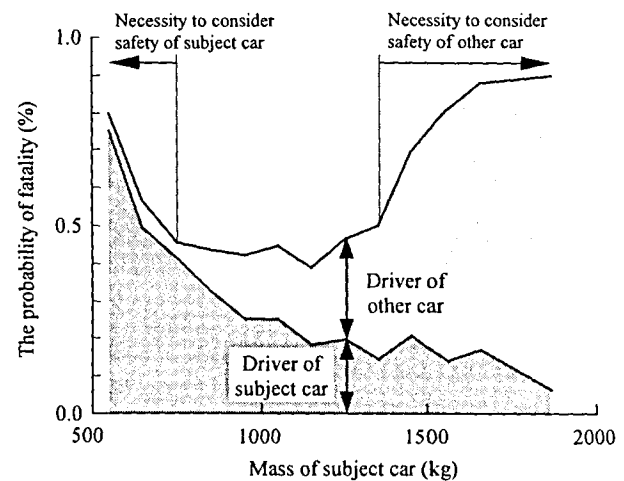


Figure 8. Car mass and the driver fatality of subject and other car in car-to-car frontal collisions.

Car classes have different mass, stiffness and geometry distributions. The effects of mass, stiffness and geometry are combined when the compatibility is analyzed by car class.

Figure 9 shows the number of driver fatalities in the subject and other car per thousand accidents. For SUV and IBOX, the total number of driver fatalities is large and the proportion of the fatalities in other cars is large, so SUV and IBOX can be considered incompatible cars. On the other hand, for mini cars, the number of fatalities in the

subject car is the largest in all car classes. Therefore, mini cars cannot be said to be compatible in car-to-car frontal collisions. The wagon and sedan B are compatible cars in car-to-car frontal collision because the proportion of the number of fatalities in the subject to that in other cars is almost the same, and the total number of fatalities in the subject and other cars per accident is small. However, the number of registrations of the incompatible car types such as SUV and IBOX is increasing, while that of sedan B, a compatible car type, is decreasing [Mizuno and Kajzer 1997].

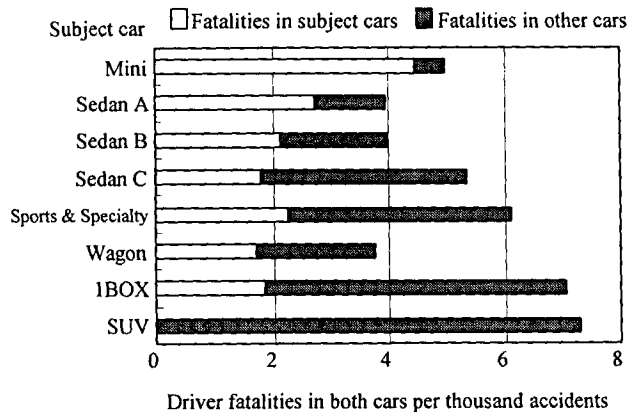


Figure 9. Car compatibility (N=531).

The aggressivity estimated by method 1 is shown in Figure 10. In this method, cars can be defined as aggressive when the aggressivity value is greater than one, because the number of fatalities in the other car is larger than in the subject car. Therefore based on Figure 10, the SUV, IBOX, sedan C and sports & specialty can be described as aggressive. According to this analysis, the aggressivity ranking of the car itself is shown as:

Mini < Sedan A < Sedan B < Wagon  
< Sports & Specialty < Sedan C < IBOX < SUV.

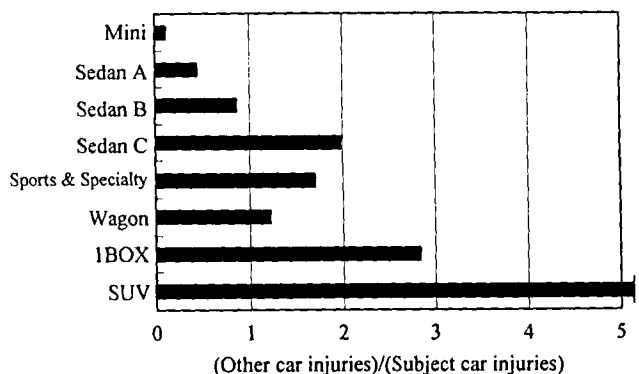


Figure 10. Car aggressivity calculated by method 1.

## Computer Simulation of Mini Car Crash

Computer simulations of a crash of a mini car were performed in order to clarify the injury risk to the driver of mini car and to examine a compatible mini car.

**Mini Car Crash into Rigid Wall** - The crash of a mini car into a rigid wall at 50 km/h was analyzed in terms of different stiffness of the mini car ( $k$ ). Figure 11 shows the variation of the acceleration, deformation of the car and the firewall intrusion with the stiffness of the mini car. The acceleration increases with the stiffness, while the deformation and the intrusion decrease. Thus when the stiffness increases, the driver is exposed to injury risk due to the high acceleration. On the other hand, when the stiffness decreases, the driver is exposed to injury risk due to the large intrusion.

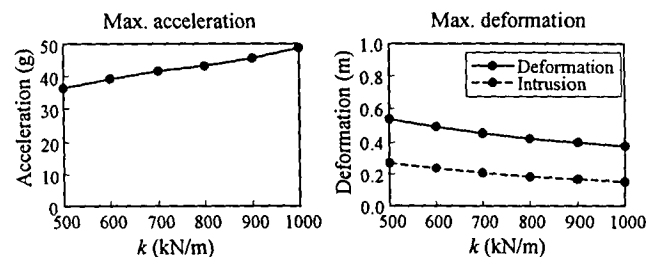


Figure 11. Maximum acceleration and deformation of mini car in crash into a rigid wall with varying stiffness of the mini car ( $k$ ).

Figure 12 shows the driver behavior where the stiffness of the mini car ( $k$ ) is 500 kN/m and 1000 kN/m, respectively. When the stiffness of the mini car is 500 kN/m, the intrusion is large but the acceleration of the car is small. As a result, the head and chest movement of the driver is less, but the foot rotation angle at 500 kN/m is greater than at 1000 kN/m.

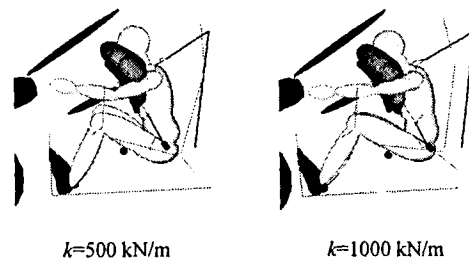


Figure 12. Kinematics of the driver in a mini car in a crash into a rigid wall (50 km/h).

Figure 13 shows the relation between the injury risk to the driver and the stiffness of the mini car ( $k$ ). When  $k$  is lowest (500 kN/m), the HIC is 706, chest acceleration (3 ms) is 55.9 g and chest deflection is 0.042 m, all of which are less than the injury tolerance levels. The HIC and

chest acceleration increase consistently with the stiffness of the mini car. On the other hand, the chest deflection, femur force, tibia axial force and moment do not change so much with the stiffness of the mini car, and its level is less than the injury threshold. These results suggest that in a mini car crash into a rigid wall, the risk of injury to the driver decreases when the front stiffness is low.

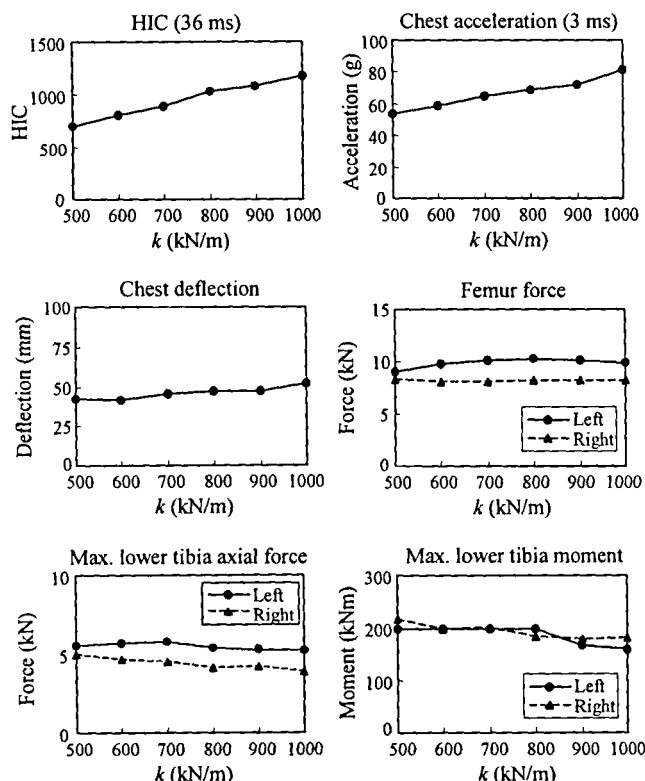


Figure 13. Driver injury risks in a crash into a rigid wall with varying stiffness of the mini car ( $k$ ) (50 km/h).

The transition to serious injuries of the lower extremities (AIS 3 or more) appears when the intrusion exceeds 0.25 m [Morris et al. 1997]. As shown in Figure 11, the intrusion of the mini car firewall is less than 0.27 m in a crash into a rigid wall at 50 km/h. Therefore, in this type of crash configuration, the intrusion is a less important factor in determining the injury risk to the driver of a mini car, whereas the acceleration causes the majority of injuries.

**Mini Car Crash into Large Car** - Simulations of an offset frontal collision between mini and large cars were carried out. The overlap ratio of the mini car is 50% and that of the large car is 40%. Figure 14 shows the deformation of the car and intrusion of the firewall by the stiffness of the mini car ( $k$ ). The acceleration level of the mini car in this type of crash is lower than in a crash into a rigid wall, whereas the car deformation and firewall intrusion of the mini car become large, especially when the

stiffness of the mini car is small. Thus, in this type of collision, the effects of the acceleration and intrusion are combined, and the risk to the driver of the mini car becomes high.

As can be seen in Figure 15, when the mini car is less stiff ( $k=500$  kN/m), the steering column, instrument panel and toe pan intrude and hit the chest, knee and foot of the driver, respectively.

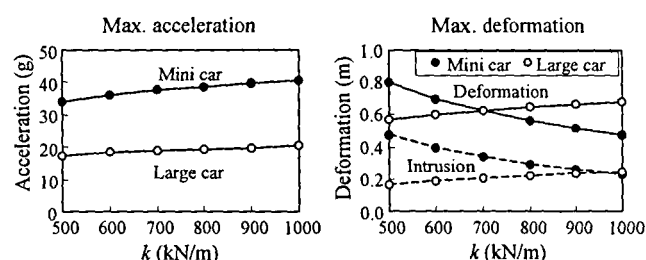


Figure 14. Maximum acceleration and deformation of mini and large cars in a car-to-car frontal collision with varying stiffness of the mini car ( $k$ ).

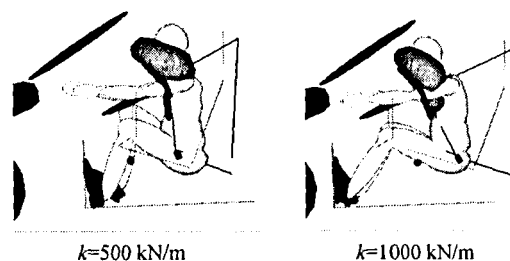


Figure 15. Kinematics of the driver in a mini car in a crash into a large car.

Figure 16 shows the variation of the injury risks to the drivers in mini and large cars with the stiffness of the mini car ( $k$ ). When a comparison is made with Figure 13 and Figure 16, the HIC and chest acceleration of the driver in the mini car are lower in a crash with a large car than into a rigid wall, whereas the chest deflection, femur force, tibia force and tibia moment are higher. The chest deflection and tibia force are strongly affected by intrusion. Thus, in a crash of the mini car with a large car, the intrusion is an important factor in injuries. In addition, Figure 16 indicates that the injury risk of the driver in a mini car is higher than for the driver in a large car, irrespective of the stiffness of the mini car. This result corresponds to the findings from accident analysis that the injury risk to the driver in a mini car is high, while in a large car is low as shown in Figure 9.

When the stiffness of the mini car increases, there is a decrease in the risk to its driver as estimated on the basis of intrusion criteria such as chest deflection, maximum femur, tibia force and tibia moment. However, the HIC and chest acceleration of the driver in the mini car increase with the stiffness of the mini car because its acceleration becomes

high.

As the stiffness of the mini car increases, the risk of injury to the driver in a large car tends to become greater. When the stiffness of the mini car is high, the chest acceleration, chest deflection, femur and tibia forces of the driver in the large car increase because both acceleration and intrusion of the large car become high. Nevertheless, the risk of injury to the driver of the large car is less than that of the driver of the mini car, and even less than the tolerance level of the relevant injury criteria.

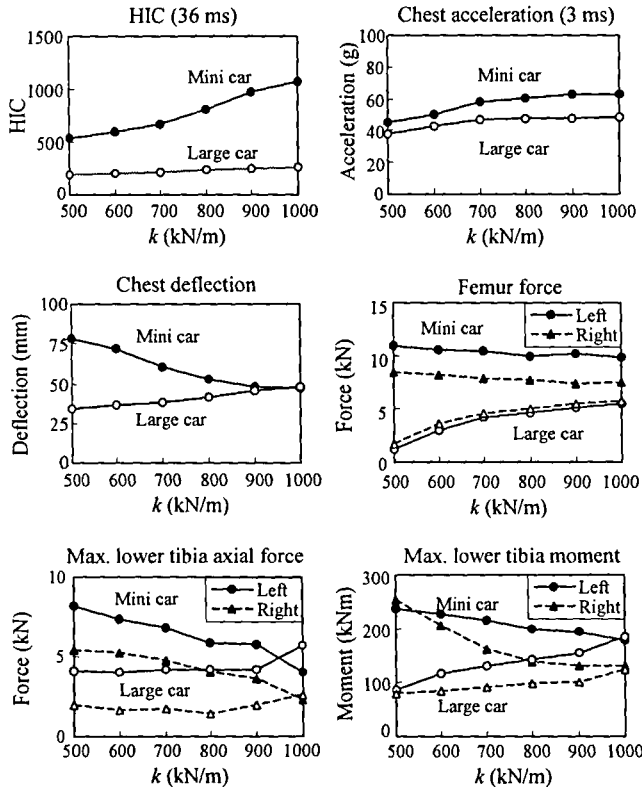


Figure 16. Driver injury risks in mini and large cars in a car-to-car frontal collision with varying stiffness of the mini car ( $k$ ).

This analysis of collisions between mini and large cars demonstrates that the mini car should be stiff enough to prevent a large intrusion into the passenger compartment in a car-to-car frontal collision because greater intrusion means a higher risk of chest deflection and injury to the driver's lower extremities.

**Effect of Restraint Systems** - It is possible that the injury risk of the driver in mini car is reduced by the restraint system despite its high acceleration. In the current study, the stiffness of 1000 kN/m is applied for the mini car because the chest deflection, femur, tibia forces and tibia moment become low at this stiffness level as shown in Figure 16.

We evaluated the injury-reducing effect of the restraint systems (seat belt force limiter, energy absorbing

steering system, knee bolster and their combination) on the driver of the mini car, in comparison with the results when an airbag and seat belt are simulated as a basic restraint system.

Figure 17 and Figure 18 show the effect of restraint systems on the injury criteria of the driver of a mini car in crashes into a rigid wall and a large car, respectively. The

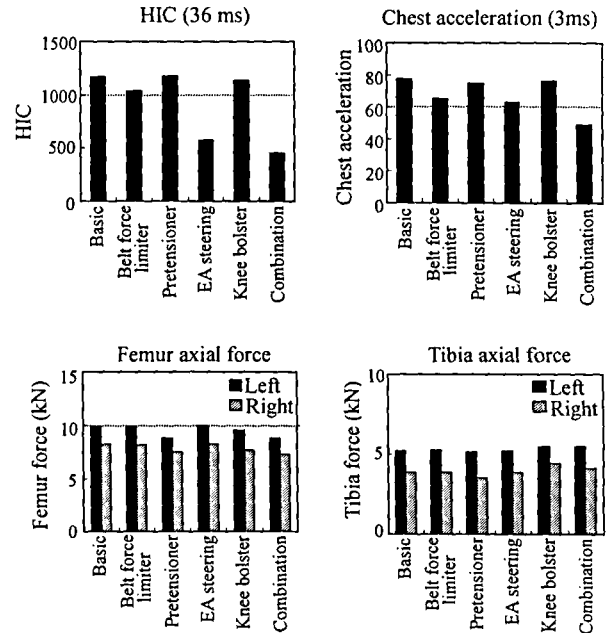


Figure 17. Effect of the restraint systems on the injury risks to the driver of the mini car in a crash into a rigid wall ( $k=1000$  kN/m).

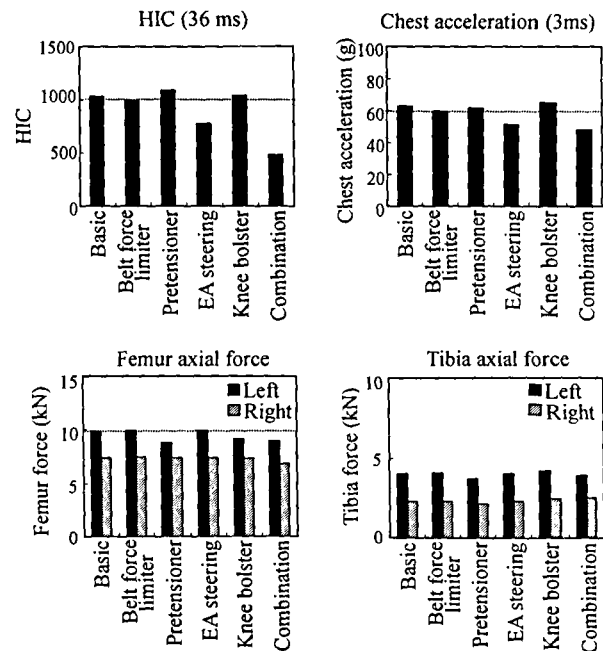


Figure 18. Effect of the restraint systems on the injury risks to the driver of the mini car in a collision with a large car ( $k=1000$  kN/m).

injury-reducing effect of each restraint system for the driver of mini car differs between the two kinds of crashes. In the crash into the rigid wall, the seat belt force limiter effectively decreases chest acceleration and HIC by reduction of force transfer from the seat belt to the torso of the driver. Nevertheless, the force limiter has a small effect on the injury risks of the driver of the mini car in collision with a large car. In this type of crash, a large force is applied to the driver's chest by the steering wheel, not by the seat belt. Thus, the seat belt force limiter has a small effect on reduction of the chest acceleration in a collision with a large car.

The EA steering system is effective for both of the above-mentioned crashes. The movement of the steering column can decelerate the driver's head and chest by absorption of energy. The seat belt pretensioner reduces the femur force. The knee bolster also reduces the femur axial force, particularly in a crash with a large car. The restraint systems have little influence on the tibia force of the driver in a crash into a rigid wall or a collision with a large car. Thus, to reduce the tibia forces, the intrusion of the toe pan must be reduced.

When a mini car with high stiffness is equipped with restraint systems combining airbag, seat belt force limiter with pretensioner, EA steering system and knee bolster, the injury criteria levels for the driver are below the thresholds in either crashes into a rigid wall or a large car.

**Additional Crush Space of Large Car** - The additional crush space of the large car reduces the injury risk to the driver in the mini car due to reduction of acceleration and intrusion of the mini car in a collision. Figure 19 shows the chest acceleration, chest deflection, femur and tibia forces of drivers in the mini and large cars in terms of the length of additional crush space ( $c$ ) of a large car (200 kN). The additional crush space reduces the chest acceleration and femur force of the driver in a mini car, when the stiffness of the mini car ( $k$ ) is high. Particularly when  $k$  is small, the chest deflection and tibia force of the driver in the mini car decrease due to the small intrusion into the mini car, as the additional crush space of the large car increases. Therefore, the additional crush space of a large car has an injury-reducing effect on the driver of the mini car by reducing the acceleration and the intrusion of the mini car.

The chest acceleration of the driver in a large car decreases when the additional crush space of the large car is large due to the low acceleration of the large car. The chest deflection slightly increases by the additional crush space of the large car. The femur and tibia forces of the driver in the large car increase with the additional crash space of the large car, and have large values when the mini car is stiff. Thus, the analysis indicates that the additional crush space of the large car is effective in reducing injury risk to the

driver of the mini car. However, when the mini car is stiff, the risk to the driver in the large car, especially for injuries to lower extremities, becomes high.

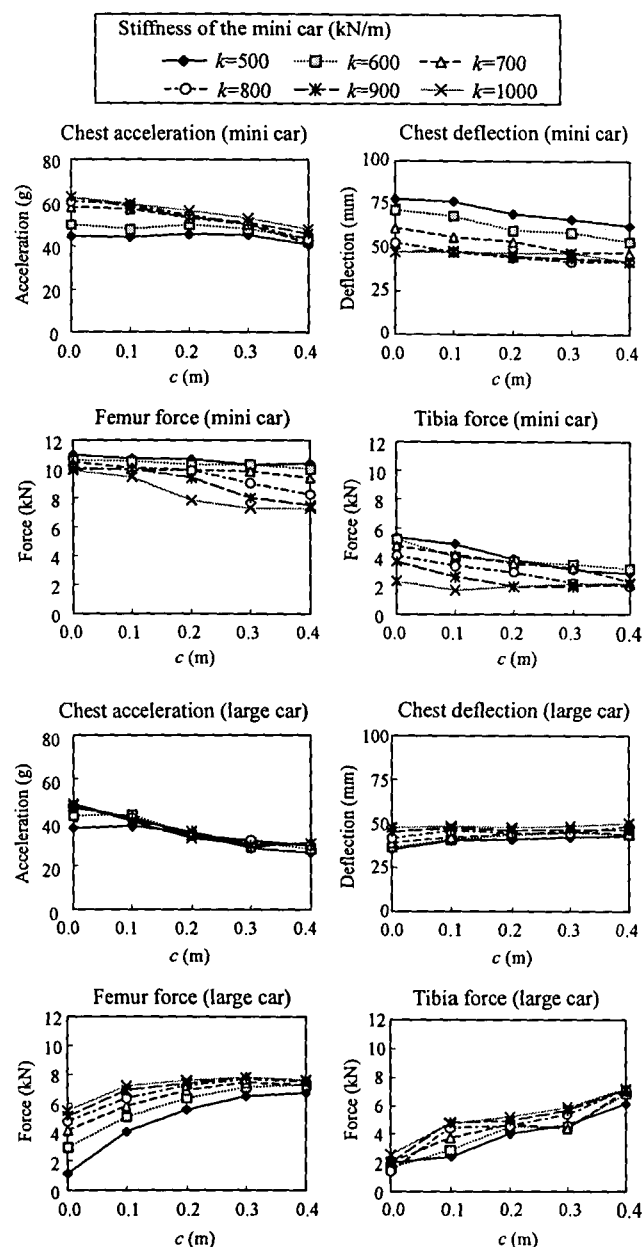


Figure 19. Driver injury risks in mini and large cars with the length of additional crush space ( $c$ ) of the large car.

## Car-Pedestrian Accidents

**Accident Analysis** - In car-pedestrian accidents, the vehicle geometry affects the injury risk to the pedestrian. Figure 20 illustrates the distribution of pedestrian injuries per thousand accidents by body region, injury severity and



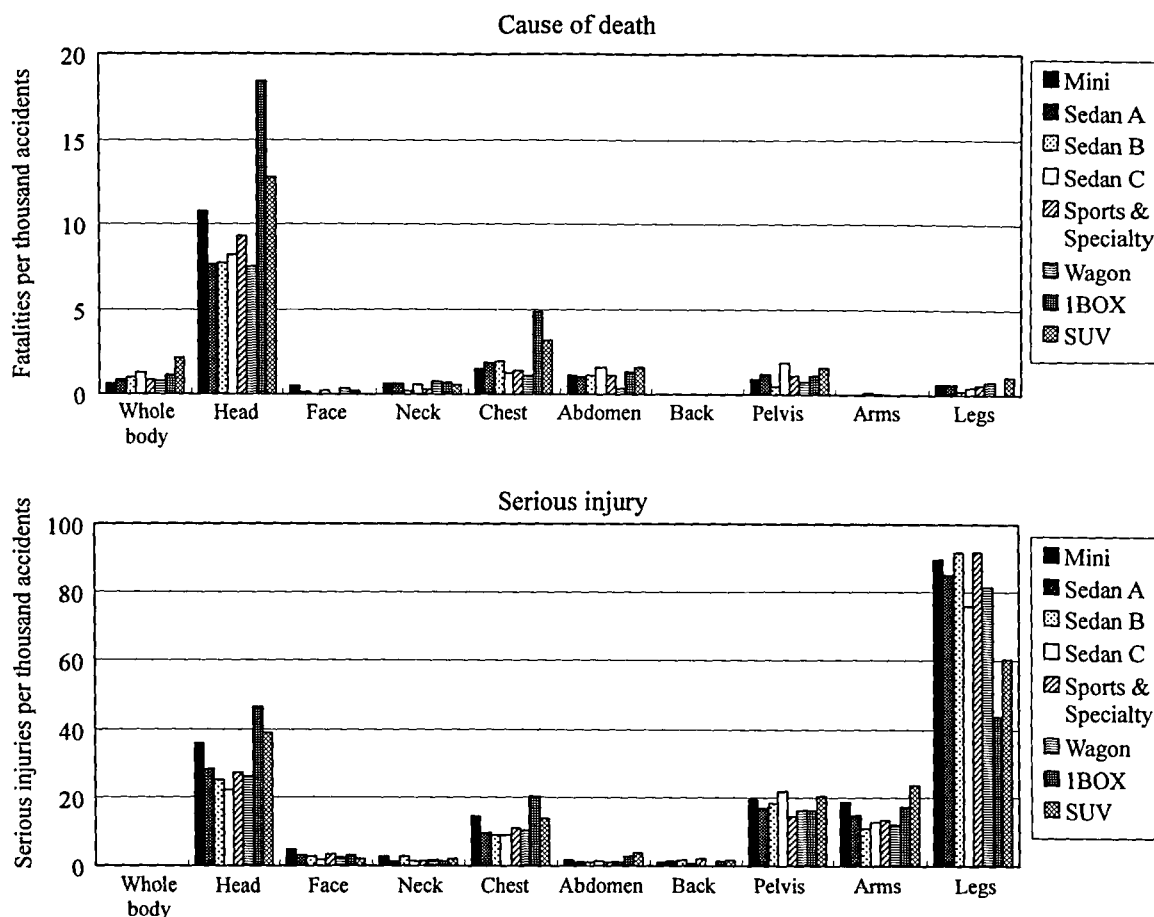


Figure 20. Distribution of pedestrian injuries per thousand accidents by body region, car shape and injury severity for the velocity recognized to be dangerous  $\leq 40$  km/h and pedestrian aged 13 or more (1994-1996).

car class. To exclude high-velocity collisions, especially between sports & specialty cars and a pedestrian, the velocity recognized to be dangerous was limited to 40 km/h or less.

The head is a dominant body region in fatalities for all car classes. The number of fatalities due to head and chest injuries is about two times larger for IBOX than for bonnet-type cars (mini, sedan A, B, C, sports & specialty and wagon). In a serious injury, the number of head and chest injuries which can be a cause of death is larger for IBOX than for a bonnet-type car. Therefore, it is considered that the front shape of IBOX is more aggressive for a pedestrian than that of a bonnet-type car. However, the shape of a bonnet-type car is aggressive in relation to pedestrian legs because the number of serious leg injuries is large in crashes with this type of car.

The risk of head injury to pedestrian when struck by a mini car is higher than for other bonnet-type cars. The SUV has a high aggressivity in relation to the head and chest of the pedestrian due to the height of the hood edge and bumper and the high stiffness of the vehicle body. As the

body front shape affects the distribution of pedestrian injuries, the modification of the shape of the car front can be effective to increase the compatibility between car and pedestrian.

**Simulation of Car-Pedestrian Accidents** - Computer simulations were carried out for crashes of mini car, sedan B and IBOX with a pedestrian. Figure 21 shows the pedestrian kinematics when the head of the pedestrian contacts the vehicle body. The kinematics differs when the pedestrian is struck by vehicles with different front shapes.

When a pedestrian is struck by a mini car or sedan B, the bumper hits the leg and the hood edge hits the thigh, then the upper torso of pedestrian rotates toward the hood of the car. The pedestrian's head contacts the windscreen when hit by a mini car, and the cowl area when hit by sedan B. With a IBOX vehicle, the whole body of the pedestrian is struck by the vehicle front almost at the same time. The chest contacts the upper part of the front panel, the head contacts the lower part of the windscreen, and then the whole pedestrian body is projected ahead of the vehicle. The pedestrian kinematics when struck by a vehicle is

influenced by the translational and rotational movement of the pedestrian. With a mini car and sedan B the rotational movement is dominant, while with a 1BOX the translational movement is dominant.

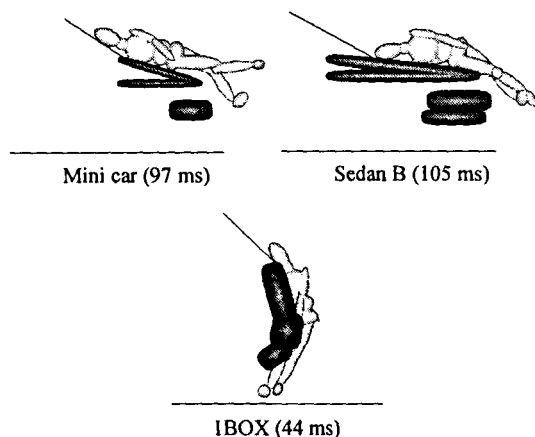


Figure 21. Pedestrian kinematics when the pedestrian head contacts the car body.

HIC is affected by the head resultant velocity at impact as well as the stiffness of the vehicle body area where the head makes contact. The time history of the head resultant velocity varies with vehicle shape. Figure 22 shows the head resultant velocity in relation to the respective car class. As shown in this figure, when the pedestrian is struck by a 1BOX, the head resultant velocity decreases consistently. When struck by the mini car and the sedan B, the head resultant velocity increases gradually due to the rotation of the upper body of the pedestrian, decreases gradually, and then drops abruptly after the pedestrian's head contacts the car body. For a mini car, the head contacts the windscreen in such an early phase that the head resultant velocity at impact is high.

The injury risk to the pedestrian body region differs with the shape of the car impacting it. The injury parameters of the pedestrian are HIC, chest, pelvis and thigh accelerations (3 ms) as shown in Figure 23. The HIC is the highest for sedan B due to the high resultant velocity at impact and the high stiffness of the cowl area where the pedestrian head makes contact. When the pedestrian is struck by a mini car, the HIC is lower than sedan B due to low stiffness of the windscreen. The chest and pelvis accelerations are highest when struck by 1BOX compared with other cars. The thigh acceleration is higher for sedan B and mini car than 1BOX. The distribution of injury risk to the chest and leg by car class agrees with those of real-world accidents (Figure 20.). However, in real-world accidents, the injury risk to the pedestrian head is highest when struck by a 1BOX, followed by a mini car and a sedan B. This differs from the simulation results.

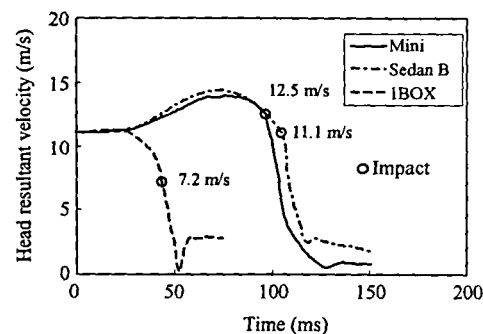


Figure 22. Head resultant velocity.

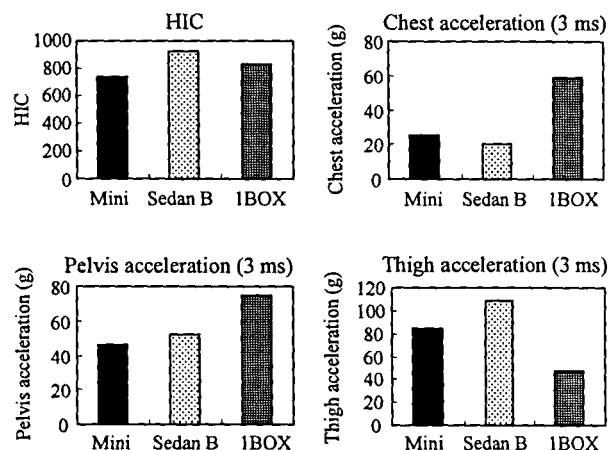


Figure 23. Injury risk to the pedestrian when struck by a car.

## DISCUSSION

### Mini Car Crash

The number of fatalities per registered mini car in real accidents is small, so the mini car may be considered compatible. However, in the method used in the present study, the injury risk to the driver in the mini car is underestimated since the accident rate and crash velocity of this type of car are low. When the injury risk to the driver is estimated by the probability of fatal injury, it is clear that the mini car is an incompatible car type because of the high fatality rate of the driver. Computer simulations of car-to-car frontal collisions also indicate that the injury risk to the driver in a mini car is far higher than in a large car.

This high injury risk to the driver of the mini car in a collision with a large car cannot be evaluated by the crash test into a rigid wall that is currently required by law. In a crash into a rigid wall, there is no influence of car mass on the injury risk to the driver and the influence of intrusion is small. However, in a collision with a large car, the driver of the mini car is at high risk of injury due to the high acceleration and large intrusion based on its small mass and size.

Two methods are considered to reduce the injury risk to the driver of a mini car. The first is to stiffen the mini car. Since the acceleration of this car tends to be high, optimized restraint systems combining airbag, seat belt force limiter, pretensioner, EA steering system and knee bolster is necessary. The stiff front structure and special restraint systems of the mini car can directly reduce the injury risk of the driver. In this method, no modifications of the large car are necessary to reduce the injury risk to the driver in the mini car. However, the aggressivity of a stiff mini car should be considered not only in car-to-car frontal collision but also in other types of collisions, such as side and rear-end collisions. In a low-velocity crash in which the airbag should not deploy, the risk of minor injury to the driver in the stiff mini car may increase due to high acceleration.

The second method is to provide a large car with additional crush space designed for a crash with a mini car. It is possible that by reducing the acceleration and the intrusion of the mini car, the injury risk to the driver in the mini car would be reduced. Thus, in both cases, whether the mini car is less stiff or stiff, this additional crush space in a large car is effective to reduce the injury risk to the driver of the mini car. On the contrary, the additional crush space of the large car causes intrusion into the large car, so the injury risk to the driver of the large car, particularly to the lower extremities, increases, when the mini car is stiff.

#### Car-Pedestrian Accidents

The accident data obtained in the present investigation demonstrate that the pedestrian has a high risk of head injury when struck by a 1BOX or a mini car. In the simulation, when struck by a 1BOX and a mini car, the HIC of the pedestrian is not so high because the head contacts the windscreen. The average elderly pedestrian aged 60-69 was used for the model. In the real mini car-pedestrian accidents, the head may contact the stiff part of the car such as windscreen frame and cowl area when the stature of the pedestrian is shorter than average or the velocity of the mini car is less than 40 km/h. As the width of the mini car is small, there is a high risk of the pedestrian striking A pillar of the car, or to be thrown away from the hood to the ground. When struck by a 1BOX vehicle, the pedestrian will often sustain a head injury because of being thrown to the ground following impact.

The simulation results show that the HIC of the pedestrian is small when his or her head contacts the windscreen. The mini car should be safety-engineered by designing the vehicle configuration so that should it strikes a pedestrian any contact of the head will be with the windscreen, no matter how large or small the pedestrian and for a wide range of impact velocity.

#### CONCLUSIONS

Mini car compatibility issues were discussed for car-to-car frontal collisions and car-pedestrian accidents using traffic accident data in Japan and computer simulations.

The results of the accident analysis for car-to-car frontal collisions are as follows.

1. A car with mass of 1150 kg is considered most compatible among the current car population in Japan. This compatible car mass coincides with the average mass of cars in Japan.
2. The SUV and mini car are the least compatible car types, with high and low aggressivity in relation to other cars, respectively.
3. Sedan B and wagon type cars are considered compatible. The proportion of the number of fatalities in the subject cars to that in other cars is almost the same, and the total fatalities in the subject and other cars are few.

Simulations of the safety of the driver in a mini car were performed using MADYMO for crashes into a rigid wall and into a large car. The following conclusions were obtained:

4. The crash test of a mini car into a rigid wall is insufficient to assure safety in a crash into a large car. This is because in a crash into a rigid wall the acceleration greatly influences the risk of injury to the driver of a mini car, whereas in a crash with a large car the effect of intrusion as well as acceleration is large.
5. The combination of the restraint systems in conjunction with high stiffness of the mini car provides good protection for the driver in either crashes into a rigid wall or a large car.
6. When a large car has additional crush space, it is effective for reduction of the injury risk to the driver in the mini car. However, if the mini car is stiff, the driver of the large car risks chest and leg injury due to the intrusion into the large car.

The accident analysis and simulation of pedestrian accidents were carried out. It is concluded that:

7. Incompatibility of the car geometry with a pedestrian has a large effect on the distribution of pedestrian injuries. Accident data show high injury risk to the pedestrian when struck by a mini car. These data could not be reproduced by computer simulation where a pedestrian is impacted only by the car without considering the head impact with the ground.

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## DEMANDS FOR COMPATIBILITY OF PASSENGER VEHICLES

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### ABSTRACT:

Any discussion of vehicle compatibility represents an attempt to take an integrated approach pertaining to the numerous conflicts associated with goals related to passive vehicle safety. In order to keep the complexity of such a discussion within manageable limits, it would appear appropriate to concentrate on the most relevant collision modes. Compatibility characteristics are observed in vehicle crash testing. These must also be investigated in real-world accidents to verify their relevance to injury reduction. A list of relevant compatibility characteristics is given. Although, from a theoretical point of view, stiffness should be a dominating factor, it is difficult to find this in real-world accidents. A "bulkhead" concept is given as an attempt to avoid excessive crush of smaller vehicles by limiting the force level of the striking vehicle in frontal collisions. The demand for self-protection, as defined by the barrier impact speed for which the vehicle is designed, limits the range of mass ratios, for which the bulkhead concept can be established. An over-view of ongoing compatibility research by automotive industry is given. One of the goals of this research is to classify vehicles compatibility by computer simulation, to the extent possible, and by vehicle crash testing, to the extent necessary.

### INTRODUCTION:

From a theoretical point of view, it is quite easy to talk about compatibility. Even in car-to-car crash tests there are observations such as override and under-ride of longitudinal frame members, different amounts of deformation of colliding vehicles etc. If compatibility were to be derived only from crash tests, the question of relevance for injury avoidance would still remain open. We would deal with compatibility as a certain kind of "crash-aesthetics" that deals with deformation behavior merely from an academic

perspective. For example, the purely axial collapse by pleating of longitudinal frame members is noteworthy. It is obviously the best way of absorbing energy. Other types of deformation, however, although not as effective from a theoretical point of view, should not be criticized, as long as it cannot be proven by real world accidents that this different behavior results in higher injury risk. Much effort has been expended to generate interesting accident data bases. They should be applied in research on passive safety as much as possible.

#### *Vehicle types and collision modes.*

Cars are subjected to many different collision modes:

A car may collide with an object such as a tree or a pole. It may experience a rollover. These are single vehicle accidents. No other party is involved that may be injured by the car in question. The issue in these cases was whether the vehicle was able to reasonably protect its occupants. Thus, in these cases, only self-protection is relevant.

When one car strikes another, the deformation of two vehicles can be compared - bearing in mind that the impact exposure for each vehicle is different unless the impact is head-on. The injuries in the two vehicles can also be compared. The accident may permit an evaluation as to which vehicle offers greater self-protection. There are, however, observations to the effect that some vehicles tend to produce higher injury levels in the opposing vehicle than others. Thus, a car-to-car accident may not only permit a comparison of the level of self-protection provided by the two vehicles, it may also permit identification of the hazard to which one car may be exposed in an impact with another. This potential hazard posed by a vehicle is called its aggressiveness. The inverse of aggressiveness is the ability of a vehicle, to protect the occupant of an opposing vehicle: partner protection. It is difficult to distinguish between good self-protection and good

partner protection. This can only be done based on a larger body of accident data. When an accident tends to be more severe in terms of injuries for different vehicles, when struck by a particular vehicle or type of vehicle, then there is a probability that this opponent or class of opponents is more aggressive and provides less partner-protection than the average. Fig. 1 indicates the well-known fact that larger vehicles cause higher injury levels up to now, when they are involved in accidents with smaller vehicles.

When a car is hit by a truck, the lack of partner protection for most trucks is obvious. It is even obvious for most sports-utility-vehicles. The typical result of such accidents is a high injury level in the car and minor or no injuries in the truck or SUV. Typical measures for partner-protection by trucks are under-ride guards, etc. As long as they do not exist, individual self protection measures on a passenger car to protect against trucks are nearly inconceivable.

In accident involving cars and pedestrians, a car normally strikes an unprotected person. The measures that are adequate in such a case are currently being discussed in technical groups. A pedestrian, when hit by a vehicle, will deform the vehicle only few

centimeters. Such deformation is virtually independent of the deformation that occurs in the other collision modes. This means that at least in a first phase of structural compatibility study, pedestrian accidents can be treated separately. There is no need to include them directly in a car-to-car compatibility study. This may change, when compatibility studies become more sophisticated and are able to influence the design of vehicle structures from the outset.

For two-wheeled vehicles, this is not generally true. Heavy motorcycles can pose a special hazard to a car, particularly in a significant side impact. Thus, they must also be taken into consideration with respect to passenger cars. When the occupant of a two-wheeled vehicle strikes another vehicle, the cyclist should be protected to a certain degree by special clothing and the helmet. At any case, for him a minimal amount of deformation is also needed as compared to car-to-car collisions, and in this context the situation is similar for pedestrians.

When dealing with compatibility of passenger-cars, two accident modes must be considered: single vehicle accidents and car-to-car collisions. Collisions with trucks generally demonstrate the need for under-

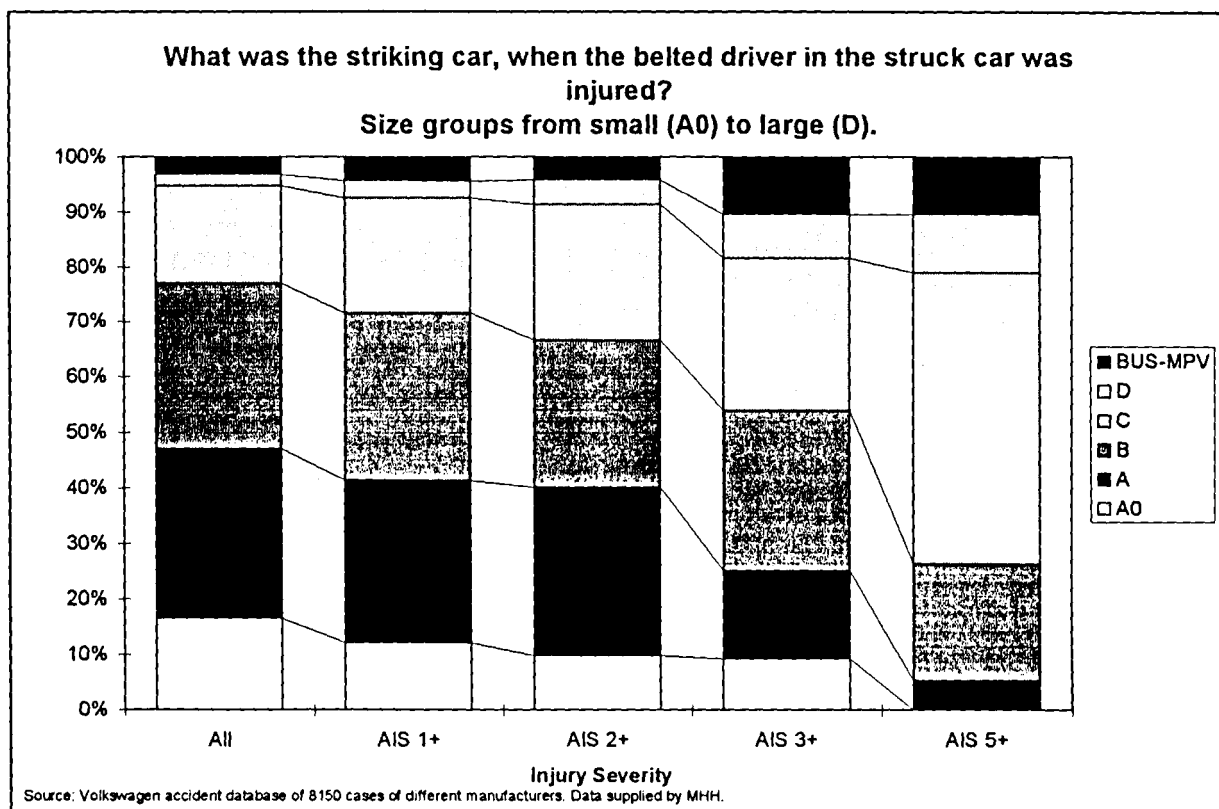


Fig. 1: Hazard of different size groups in passenger car to passenger car accidents.

ride protection by the truck. When generally accepted underride protection exists, then it makes sense to define a car structure that is compatible with the force deflection curve of the underride protection or which allows a glancing blow that prevents the car from actually impacting the truck when the collision angle is sufficiently acute. Impacts between pedestrians and two-wheeled vehicles can be understood as nearly independent of other collision modes, inasmuch as their structural demands are relevant only for the initial centimeters of the collision. These structural demands are not relevant for the behavior of a car in a single-vehicle or a car-to-car collision with a velocity change that has injury potential. On the other hand, the structural demands on the vehicle front-end to make it compatible, when striking a side of another vehicle might also be relevant for impacts with pedestrians and/or two-wheeled vehicles.

Fig. 2 depicts the accidents that are related to these collision modes with fatalities and injuries. This figure shows clearly that the single vehicle predominates as far as fatalities are concerned, and that car-to-car accidents predominate as far as injury producing accidents are concerned. Therefore, the

strategy for compatibility cannot be to optimize partner protection by decreasing self protection. The strategy for compatibility should be to optimize both partner protection and self protection in such a way that the sum of all fatalities and the sum of all injuries is minimized.

When a harmonized approach to compatibility is considered, then the American SUV problem must be kept in mind. (Gabler, 1998, Hollowell, 1996) The geometrical problems that occur in a collision between an SUV and a car are documented unambiguously by two photographs from the Insurance Institute for Highway Safety (IIHS) (fig. 3). While in frontal impact an adequate path to direct impact loads into the lower section of the SUV's front end might prevent the small car from underriding, the situation in side impact is even worse, because here the chance of a head impact against the front of the striking SUV is very likely under corresponding collision angles. The mass ratio provides additional incompatibility between these vehicles. The SUV is a vehicle with structural behavior that is in some respects similar to a car, but in other aspects similar to a truck. Therefore some of the principal countermeasures must be implemented on the

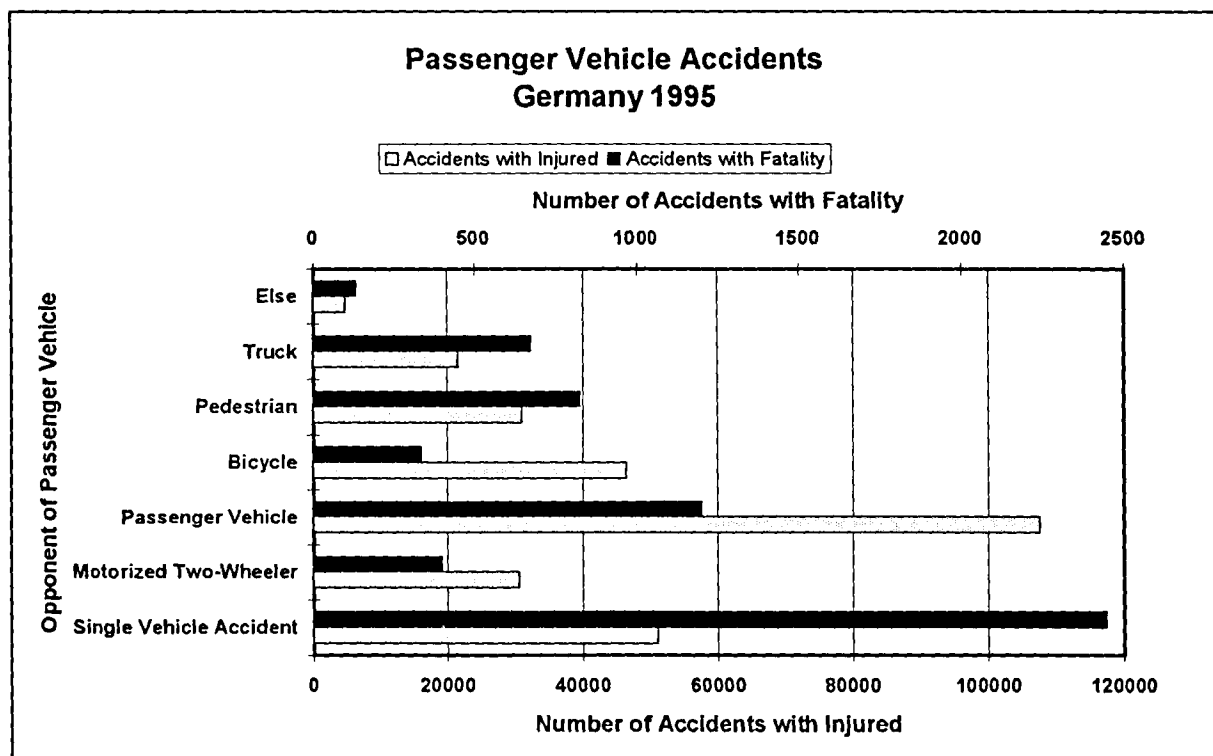
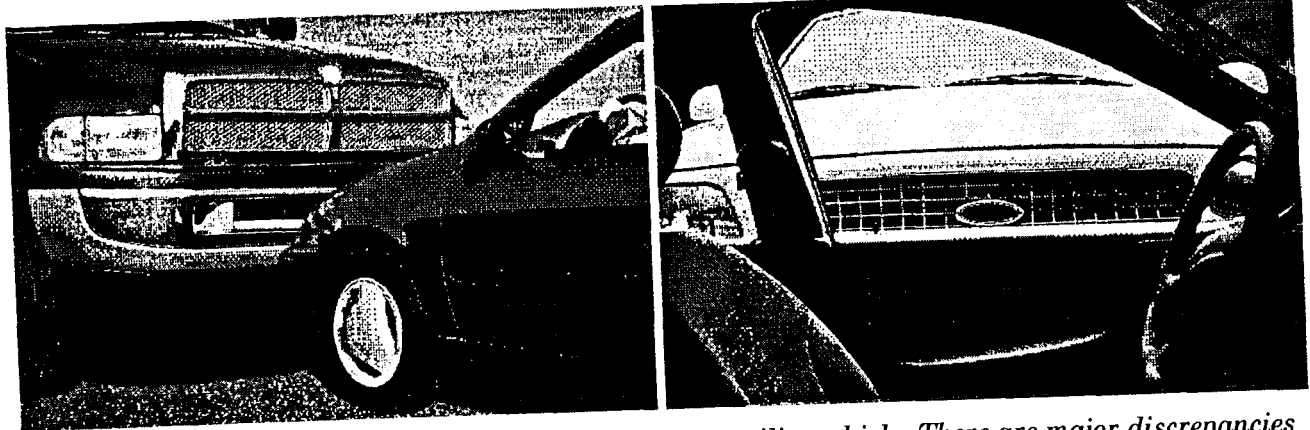


Fig. 2: Number of passenger vehicle accidents with at least one injured person involved (lower axis) compared with the number of passenger vehicle accidents with at least one fatally injured person involved (upper axis). Data are from official German statistics.



*Fig. 3: Geometrical comparison between car and sports-utility vehicle. There are major discrepancies between the two front structures and between front and side. (Courtesy of IIHS (IIHS, 1998))*

SUV as required on trucks. The mass ratio implications, however, must be resolved by the car and its restraint system. Viewed from the vantage point of larger vehicles, including SUVs etc., some authors assert that it is the small vehicle that brings about these problems. These authors tend to suggest lower limits for the mass of smaller vehicles be mandated. "Get rid of the small car" is the battle cry of this group of scientists. But, as so often with battle cries, they are not very helpful. In the future, considerations such as fuel consumption, emissions etc. will exert more pressure in the direction of smaller, technologically perfect vehicles. Thus, the existence of these two extremes of passenger vehicles must be kept in mind if compatibility is to be discussed productively. By bearing both in mind, we are also forced to deal with the different vehicle fleet existing in Europe and in Northern America. This may - we are still permitted to hope - prevent us from defining separate European and American compatibilities. By taking both aspects into account, there might be an opportunity to create a harmonized compatibility concept.

### *Compatibility characteristics*

Compatibility offers the chance to define very interesting car-to-car impact test configurations. These crash tests will have to be observed very carefully. But who is able to decide how relevant a certain observation in a crash test is for real-world accidents? There are many observations that are of potential interest with regard to compatibility, but who defines priorities among all these items?

For most researchers dealing with this subject, it is clear that from the outset that great care is

required in the analysis of accidents so that important decisions on relevance and priorities can be reached. Unfortunately, accident researchers include primarily conventional parameters about vehicles and occupants in their data bases. Accurate descriptions of structural behavior are very difficult to obtain. It is cost intensive to measure all the relevant deformation. Therefore, from the standpoint of accident analysis, priorities for compatibility features can be derived only in an indirect manner.

At ACEA (Association des Constructeurs Européens d'Automobiles), European manufacturers conducted an accident analysis to permit discussion of the relevance of compatibility features. This was accomplished by defining a list of possible compatibility features. The following items were taken into account:

- vehicle mass
- vehicle stiffness
- lateral fork effect
- vertical fork effect
- low/high vehicle front end regarding frontal impact
- high front end of the striking vehicle regarding side impact
- longitudinal engine
- transverse engine
- additionally for side impact: a well-balanced distribution of the force in the vehicle front

This list contains only the most obvious items which have been discussed in the literature thus far. The goal was and is to understand the priorities for these features for compatibility. To this end, a



combined effort was made between the ACEA Crash Compatibility Task-Force and scientists of the Technical University of Berlin. Volkswagen provided information on car-to-car accidents. The car manufacturers and the staff of Technical University of Berlin provided geometrical data on the vehicles, which were added to the database to permit some of the compatibility features to be studied.

It is not the purpose of this paper, to present the results of this ongoing research. Some of the difficulties encountered, however, should at least be mentioned: When the influence of longitudinal and transverse engines was studied, it was easy to show that vehicles with longitudinal engines tend to induce higher injury risks for a struck vehicle than vehicles with a transverse engine. Therefore, a rash conclusion would be to blame longitudinal engines for being more aggressive than transverse engines. However, a more careful look at the data discloses that vehicles with longitudinal engines tend to be larger vehicles. Thus, an adjustment was made. The database was biased towards a similar mass distribution of vehicles with longitudinal engines and vehicles with transverse engines. With this biased data set, the influence of engine orientation could be studied once more. The result was that in the biased data set, no difference between vehicles with longitudinal engines and vehicles with transverse engines could be detected. So we have no indication that engine orientation is relevant with regard to compatibility.

This result must still be verified by other data sets. It has to be verified through case-by-case analysis. The work on the compatibility feature "engine orientation" has not been finalized. This observation, however, clearly shows that accident analysis on compatibility features must be conducted very carefully. There is the dominant effect of mass. Mass of an opposing vehicle influences the velocity change of the struck vehicle under consideration. It is therefore relevant in terms of injury risk in the struck car. From what we know to date, it will be the predominant factor. All other influencing factors appear to be of minor importance or priority. This means that all other studies have to be conducted on a basis of a mass adjusted data set. Otherwise they are likely to focus upon features as incompatible that are related to vehicles of higher mass.

Some principal results should be mentioned here, but it should be noted that they are still preliminary:

- vehicle mass
  - dominant influencing factor
- vehicle stiffness
  - stiffer vehicles demonstrate slight advantages regarding self protection
- lateral fork effect
  - no results to date
- vertical fork effect
  - different height of longitudinal frame members in the colliding cars shows no disadvantages
- low/high front end of the vehicle regarding frontal impact
  - higher longitudinal frame members tend to provide lower degree of self protection
- high front end of the striking vehicle regarding side impact
  - higher sill height provides higher protection in side impact
  - higher longitudinal height provides lower partner protection in side impact
- longitudinal engine
  - no significant influence
- transversal engine
  - no significant influence
- additionally for side impact: a well-balanced distribution of the force in the vehicle front
  - no results to date

The results mentioned briefly here are the result of an accident analysis that was performed with Volkswagen data by the Technical University of Berlin (Prof. Appel and Mr. Deter). The work was initiated and funded by ACEA. It will be finalized in a compatibility project of European automotive industry and funded by the EU (BRITE-Euram).

#### *An approach to detect stiffness influences from accident data*

An attempt was made to identify differences in vehicle stiffness from accident analysis. Accident data provide the vehicle deformation index VDI. VDI6 provides an estimation of the depth of vehicle deformation (fig. 4).

In case of a car-to-car accident, two VDI6 are provided. These are compared to decide whether one vehicle excessively deformed the other. Then the VDI6 of the vehicle itself was summed for all car-to-car accidents with the particular vehicle involved. A mean value was computed. The same procedure was used for the other cars, i.e. for the opposing cars in the same

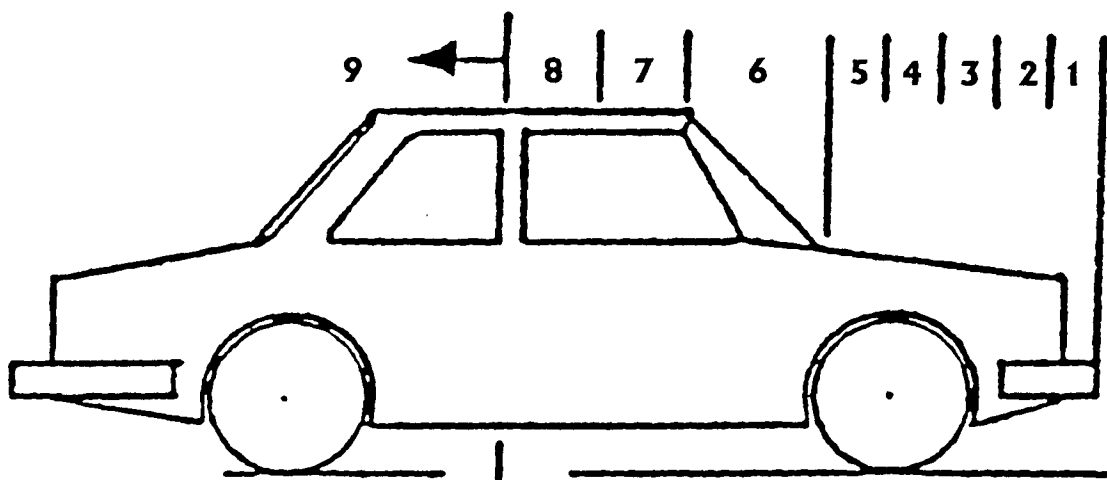


Fig. 4: Vehicle deformation index VDI for deformation extent guide (VDI6). (Source: Manual for Coding. Variables in the in-depth investigation work. Accident Research Unit, Hanover, 1990)

accident sample. Ultimately, two mean values exist, reflecting the average deformation of the car and of its opposing cars in one sample of car-to-car accidents. The difference of the two values was then computed. If it is positive, it indicates that the vehicle under consideration tends to have more deformation than its opponents - meaning that it tends to be deformed more by its opponents. If the number is negative, it indicates that the vehicle under consideration tends to have less deformation than its opponents - meaning that, it tends to deform its opponents more. This can be an indication of aggressiveness. However, before such a conclusion is drawn, this notion must be checked very carefully.

First of all, size classes are compared. A0 represents very small vehicle-models, A, B, C, D represent incrementally larger vehicle classes. There is no significant difference between A0 and A. But the other classes behave as expected (fig 5): Higher size groups tend to deform their opponents more.

The deformation comparison offers quite a different picture when model versions and different generations of models are compared. One would expect that these models should tend to become stiffer with each subsequent generation. This is true e.g. in fig. 6 for version A-A-1 to A-A-3. (Note that all names are artificial. The number refers to the model generation.) The same is true for model C-A. Its stiffness increased from generation C-A-3 to C-A-4. The other generations of this model are not relevant because of an insufficient number of accidents (1 and 2).

For size group B (fig. 7), the finding diverges even more from that which would be expected: "Newer model versions are stiffer." Model A-B shows no significant change. Model B-B shows a trend towards decreasing stiffness. The same applies to D-B. When interpreting the bars, one has to check carefully the line, which indicates the number of cases.

These findings were compared to fatalities and injuries in those cars and in their opponents. This study is not finalized, so that no conclusive results can be presented at this time. A trend is clearly evident and must be verified by carefully comparing the models involved. Neither self protection, nor partner protection appears to be strictly related to these findings. When this is true, it shows that we must exercise great care when interpreting crash test results. Higher deformation probably does not necessarily mean higher risk of injury and vice versa. This statement was checked against the maximum AIS of belted drivers, but it was also checked against injuries of body regions that are probably more sensitive to deformation, such as those of the leg and foot and those that are probably more sensitive to deceleration such as the head. Thoracic and pelvic AIS was also checked but in all cases no clear correlation was found. The same computation was made with the injuries of the belted driver of the opponent vehicle. Again no correlation was seen.

An in-depth study will be performed in order to check these preliminary results more thoroughly and, if necessary, on a case-by-case basis.

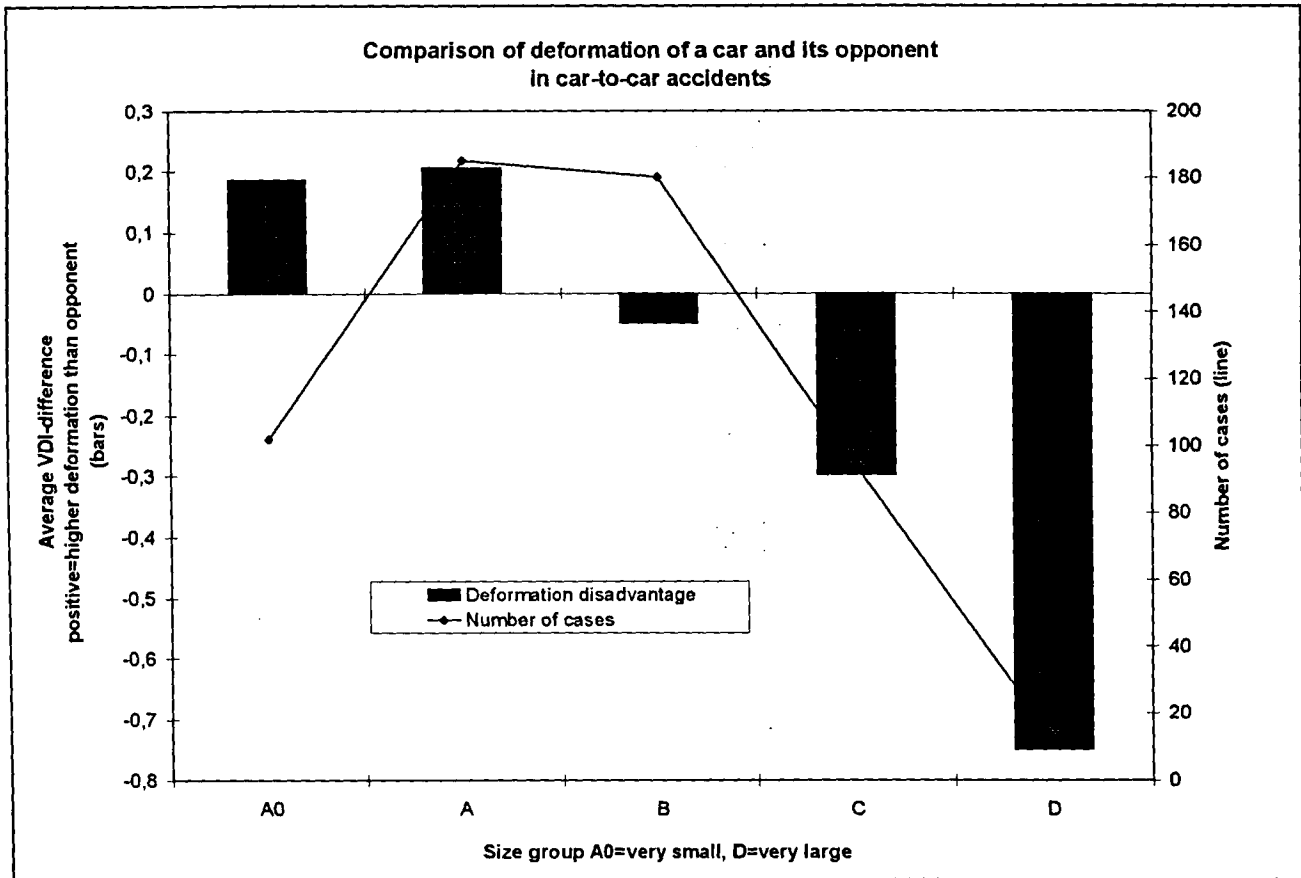


Fig. 5: The deformation behavior of different size groups, based on a comparison of VDI6 in car-to-car accidents.

### The bulkhead concept

At first glance, it would be expected that partner protection must be examined on the basis of vehicle-to-vehicle crash tests. However, before additional new crash tests are generated to prolong the list of crash tests to be performed with respect to passive safety, it must be determined whether current tests already generate information that can be used to identify partner protection. Surprisingly, the long-established test with a rigid barrier provides such information, if properly interpreted.

The test against a fixed barrier compels manufacturer to make provisions for sufficient deformation energy. If the barrier impact must be conducted with an impact velocity  $v_B$  for a vehicle with mass  $m$ , then the required deformation energy is

approximately equivalent to the kinetic energy of the barrier impact:

$$E = \frac{1}{2} * m * v_B^2$$

A frontal vehicle-to-vehicle collision can involve vehicle 1 and vehicle 2 with masses  $m_1$  and  $m_2$  and velocities  $v_1$  and  $v_2$ . The kinetic energy before the crash is

$$E_{before} = \frac{1}{2} * m_1 * v_1^2 + \frac{1}{2} * m_2 * v_2^2$$

The velocity after the crash is assumed to be the same for both vehicles  $v_{after}$ . The rebound is neglected in this example. Thus,  $v_{after}$  is computed using conservation of momentum by

$$(m_1 + m_2) * v_{after} = m_1 * v_1 + m_2 * v_2$$

This results in a kinetic energy after the crash:

$$E_{after} = \frac{1}{2} * (m_1 + m_2) * v_{after}^2$$

The lost energy is the deformation energy D in this accident

$$D = E_{before} - E_{after}$$

$$= \frac{1}{2} * \frac{m_1 * m_2}{m_1 + m_2} * (v_1 - v_2)^2$$

Thus, this well-known computation shows that the deformation energy depends on the two masses and the closing velocity  $v_c = v_1 - v_2$  of the two colliding vehicles.

The following inequation is remarkable and shows the opportunities for compatibility.

If there is a collision between two vehicles of

different masses at a closing velocity of  $v_c \leq 2 * v_B$  and if each vehicle is designed for a barrier impact with  $v_B$ , then the deformation energy of both vehicles is sufficient to sustain the collision without intrusion into the occupant compartment.

This can be proven by the following calculations: The available deformation energy of the two vehicles is

$$E = \frac{1}{2} * m_1 * v_B^2 + \frac{1}{2} * m_2 * v_B^2 = \frac{1}{2} * (m_1 + m_2) * v_B^2$$

For this collision the energy absorption will be

$$D = \frac{1}{2} * \frac{m_1 * m_2}{m_1 + m_2} * (v_1 - v_2)^2$$

$$= \frac{1}{2} * \frac{m_1 * m_2}{m_1 + m_2} * v_c^2 \leq \frac{1}{2} * \frac{m_1 * m_2}{m_1 + m_2} * (2 * v_B)^2$$

It has to be proven that  $D \leq E$ . This can be derived from the following calculations:

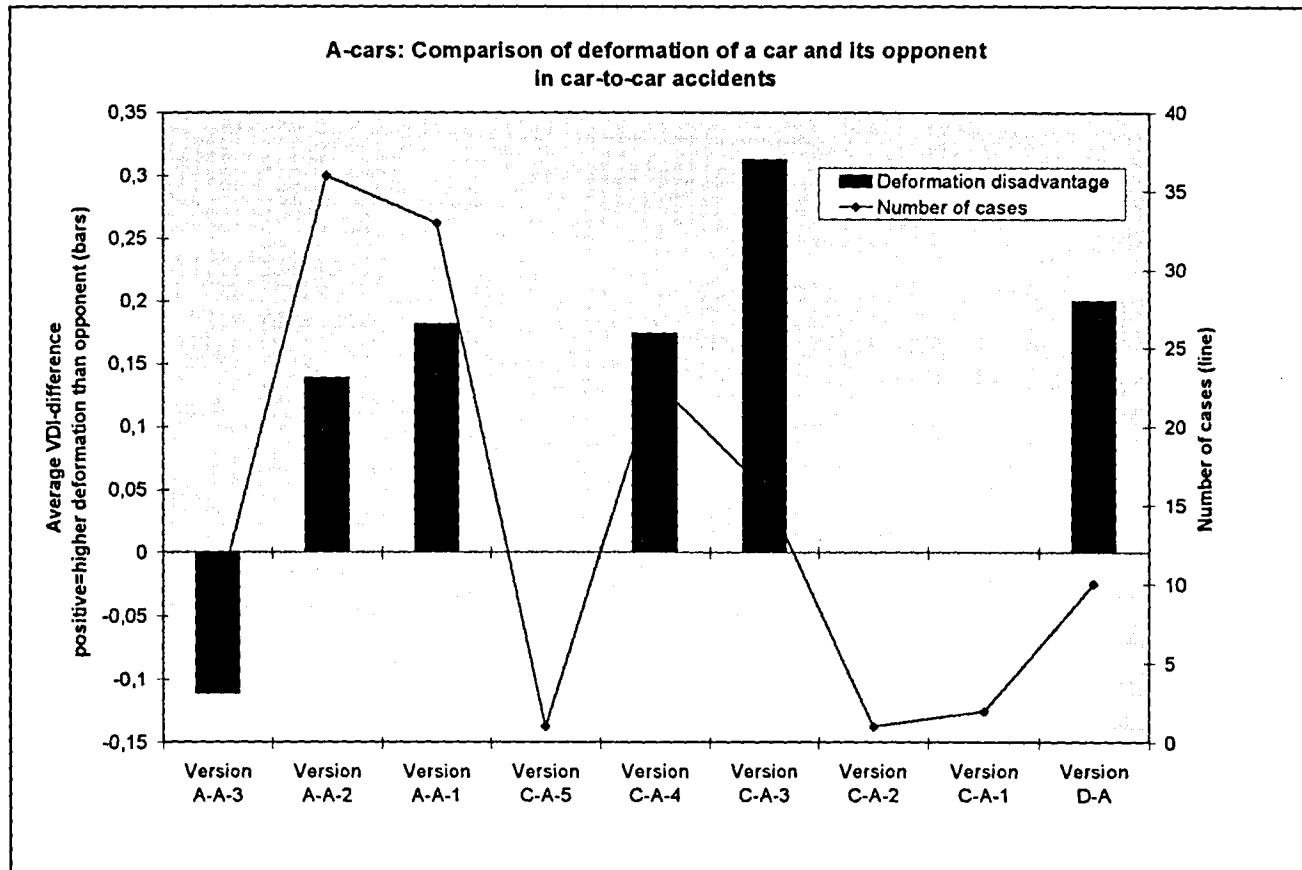


Fig. 6: The deformation behavior of size group A, due to a comparison of VDI6 in car-to-car accidents.

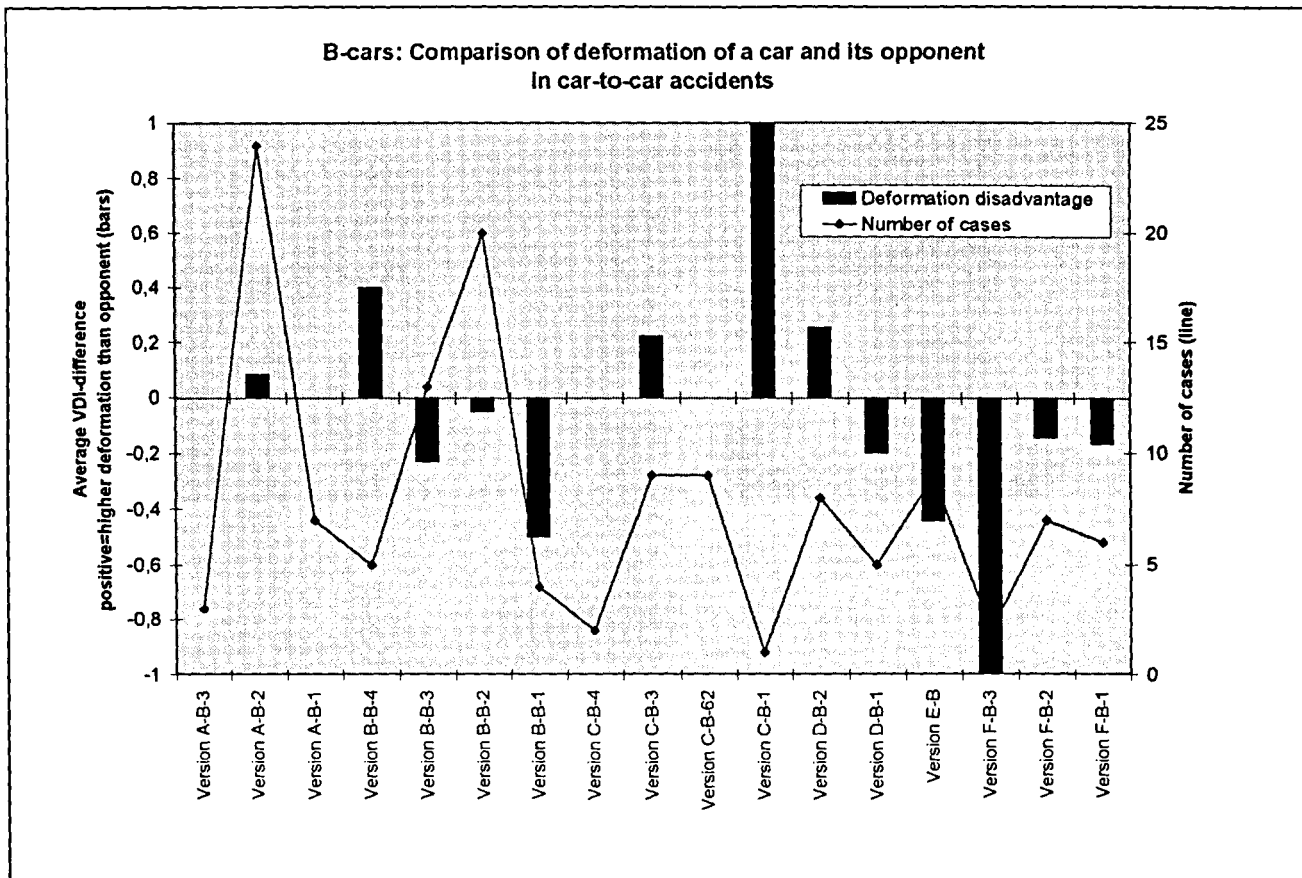


Fig. 7: The deformation behavior of size group B, based on a comparison of VDI6 in car-to-car accidents. (Carefully check the number of cases, when interpreting the results.)

Obviously a square is always positive:

$$(m_1 - m_2)^2 \geq 0$$

This means that

$$m_1^2 - 2 * m_1 * m_2 + m_2^2 \geq 0$$

holds. By adding  $4 * m_1 * m_2$  it can be seen that

also

$$m_1^2 + 2 * m_1 * m_2 + m_2^2 \geq 4 * m_1 * m_2$$

holds. As a consequence of this

$$(m_1 + m_2)^2 \geq 4 * m_1 * m_2$$

or dividing by  $(m_1 + m_2)$

$$m_1 + m_2 \geq \frac{4 * m_1 * m_2}{m_1 + m_2}$$

From this

$$\frac{1}{2} * (m_1 + m_2) * v_B^2 \geq \frac{1}{2} * \frac{m_1 * m_2}{m_1 + m_2} * (2 * v_B)^2$$

The result of this is a basic finding on compatibility:

$$D = \frac{1}{2} * \frac{m_1 * m_2}{m_1 + m_2} * v_c^2 \leq \frac{1}{2} * \frac{m_1 * m_2}{m_1 + m_2} * (2 * v_B)^2 \leq \frac{1}{2} * (m_1 + m_2) * v_B^2 = E$$

as long as  $v_1 - v_2 = v_c \leq 2 * v_B$ .

The computation looks rather theoretical, but the result has practical consequences. It is a fundamental relationship between the design speed of two vehicles and the deformation energy that is needed when the two vehicles collide:

When two vehicles collide, and if their closing velocity is less than their doubled design speed, then

there is sufficient deformation energy available for this particular crash. This holds regardless of the mass-ratio of the two vehicles.

This means for vehicles with 50 km/h design speed: When they collide with a closing velocity of not more than 100 km/h, then compartment collapse, even of the smaller vehicle, can be avoided, because sufficient energy absorption is possible, sufficient deforming material is available. This finding holds, regardless of the mass ratio. This restricts the problem of compatibility to the question: Are we able, to compel both vehicles to deform?

Looking at real world crashes, very different types of deformation can be seen: Sometimes both vehicles deform similarly, sometimes one of the vehicles looks very good, while the other vehicle is completely destroyed. The second case is typical for a crash between a very stiff vehicle and a very soft vehicle. The question arises, what is a stiff vehicle, and what is a soft vehicle? Was the undestroyed vehicle too stiff or was the destroyed vehicle too soft?

The bulkhead concept means that we define a force level that is the maximum force-level for front-end of a car to deform. A bulkhead has to be built which is able to sustain this maximum force level. This bulkhead would avoid a compartment collapse, as long as one of the vehicles is still deforming.

The bulkhead concept would force both vehicles to deform. It takes advantage of the fact that sufficient deformation energy is available. It will decide the question of too stiff and too soft. Forces up to the maximum force-level are acceptable. Everything else is too stiff. If we had already a bulkhead concept, all collisions up to a closing velocity of  $2 \cdot v_B$  would occur without excessively deforming one of the collision partners, regardless of the mass ratio. This is possible, because the fundamental relationship of compatibility, derived above, holds.

But unfortunately, there are

### ***Limitations to the bulkhead concept***

A consequence for barrier impact speed will be shown here:

When a (small) car with mass  $m_s$  collides with another vehicle with deformation force  $F$ , then for the deceleration  $a_s$ , the following equation holds:

$$m_s \cdot a_s = F$$

For the large vehicle with mass  $m_l$ , which is designed for a barrier impact speed  $v_B$ , we need deformation energy  $D$ , which is sufficient to compensate the kinetic energy at barrier impact test speed:

$$D = \frac{1}{2} \cdot m_l \cdot v_B^2$$

On the other hand, deformation energy is computed by

$$D = \int F(s) ds = F \cdot s_l$$

with deformation travel  $s_l$  of the large vehicle.

The equation only holds for the average force level  $F$  of the force deflection curve of the large vehicle's front structure.

$$\frac{1}{2} \cdot m_l \cdot v_B^2 = D = F \cdot s_l$$

$$\left( \frac{1}{2} \cdot m_l \cdot v_B^2 \right) / s_l = F$$

When this large vehicle and the small vehicle mentioned above collide, then by the principle of action and reaction the forces are equal. This can be assumed by neglecting dynamic effects that more or less produce oscillation for which the static approach generates the average behavior. Thus, the static computation is more or less a lower limit of the dynamic computation. It leads to

$$\left( \frac{1}{2} \cdot m_l \cdot v_B^2 \right) / s_l = F = m_s \cdot a$$

or

$$\frac{1}{2 \cdot s_l} \cdot \frac{m_l}{m_s} \cdot v_B^2 = a$$

This shows a relationship between barrier impact speed, mass ratio, and the available deformation stroke of the large vehicle. It is clear that there exist limits of feasibility for the deformation stroke. The length of vehicles must be restricted for several reasons, including those of an environmental nature. The deceleration of the vehicles must be restricted, because the restraint system is able to load the occupant in an acceptable manner only in case of a vehicle deceleration within certain limits.

Therefore, there is a relationship between these principal vehicle parameters, as long as we want to keep the question of compatibility in mind. One question is, what average deceleration we can permit for a vehicle, especially for a small vehicle? We should keep in mind that we are speaking about the average deceleration of the compartment. Today, with a compartment deceleration of 20 – 25 g we already need good restraint systems to achieve acceptable occupant loadings. A compartment deceleration of 30 g is already an upper limit in terms of acceptable dummy loads. Furthermore, this level of 30 g is probably not acceptable with respect to older vehicle occupants.

Now, it is easy to compute, what  $v_B$  is acceptable, as long as compatibility is possible. If we use a mass ratio of up to  $\mu = \frac{m_1}{m_s} = 1,6$ , it does not describe all vehicle-to-vehicle mass combinations, but covers approximately 90% of all frontal collisions in real-world accidents (in Germany). A deformation distance of  $s_f = 0,7 \text{ m}$  is higher than available deformation travel in the current fleet. If we accept a deceleration of 30 g that is higher than current restraint systems permit, then we find

$$30 \text{ g} = \frac{1}{2} \cdot 1,6 \cdot \frac{v_B^2}{0,7}$$

$$v_B = 16 \text{ m/s} = 57,8 \text{ km/h}$$

When we take into account that the 30 g level is an upper limit and that a mass ratio of 1,6 does not cover the whole fleet, than we must accept, that current barrier test speed is at the upper limit. 56 km/h, the NCAP test speed for FMVSS 208 is already equivalent to the EES which is achieved when 64 km/h test is performed against a deformable barrier. Therefore, an increased barrier impact speed represents an additional decrease of the possibilities for compatibility. If test speed would be increased to 60 km/h, then the mass ratio for which compatibility measures are possible will decrease by the formula

$$30 \text{ g} = \frac{1}{2} \mu \cdot \frac{(60 \text{ km/h})^2}{0,7}$$

$$\mu = 1,48$$

If test speed were to be increased to 64 km/h, then the analogous computation leads to a mass ratio of  $\mu = 1,30$ . This means that compatibility is only

possible in the range of 1000 kg to 1300 kg vehicles, e.g. that is not sufficient. When, by reason of environmental considerations, we can expect that small and fuel efficient vehicles will have an increasing market share, then we must allow for a larger compatibility range. For details compare Zobel 1997 and Zobel 1998.

### *The VDA-approach on compatibility*

VDA, the Association of the German Car Manufacturers has developed an approach on compatibility testing that is based on the ADAC-approach. (ADAC is the General German Automobile Club) (Klanner, 1998). This proposes a deformable barrier to test the deformation of the barrier, when impacted by the vehicle. The barrier should provide sufficient deformation that no vehicle bottoms out. From the amount of barrier deformation, the deformation energy provided by the barrier can be estimated. The assumption is that at a fixed test speed, stiffer vehicles produce more deformation to the barrier. Thus, the deformation of the barrier is taken as an estimation of the aggressiveness of the vehicle's front structure. Furthermore, the force behind the deformable barrier is also measured.

This approach offers good information to evaluate the load distribution in the front of a vehicle. If the vehicle has only two stiff longitudinal frame members and nothing in-between, then the shape of the deformed barrier will show this. The shape observed is very sensitive to the force-deflection curve of the barrier.

This approach, however, leaves some open questions, which could probably be answered by rigid barrier testing. The force behind the barrier is a consequence of the interaction between barrier and car. If the vehicle shows only little deformation, then the question remains as to whether this happened because the vehicle was only slightly stiffer than the barrier or whether it indicates an absolutely stiff vehicle. The deformable barrier will indicate a higher stiffness. But if this high stiffness occurs, it provides no information about the undeformed part of the vehicle. This information is needed when we think about the ability of vehicles to force potential opposing vehicles to deform and about the ability to be forced by opposing vehicles to deform.

This approach answers some of the questions about compatibility, others remain. This is probably a short term approach which may be enhanced in the

future. For this purpose, a major compatibility project has been established.

### *Basic ideas of the EUCAR-project on compatibility*

This compatibility project is a pre-normative project with the objective of minimizing fatalities and injuries in the vehicle fleet by taking into account self protection and partner protection. Analysis of the interaction of the structures of colliding vehicles with regard to injuries in the striking and in the struck vehicle will be made through hardware testing and computer simulation. The goal is the development of common design rules to achieve an optimum structural interaction between vehicles. This goal will be achieved through requirements relating to implications of vehicle structure, such as restricted force levels, dummy loads, etc.; it is not to be understood as a restriction on design options. It is to be achieved to the extent possible through computer simulation with finite element models (FEM).

Accident analysis is performed, to identify vehicles or vehicle groups that are statistically remarkable, positively through a low injury level or negatively through a high injury level in the vehicle itself or in the struck vehicle. Hardware tests are performed to reproduce the findings from accident statistics, and to verify measurable differences between statistically positive and negative vehicles. Finite element modeling (FEM) is performed to reproduce test results, to replace hardware testing where possible by FEM, and to use FEM as an additional tool to identify findings from accident analysis. The knowledge of these steps is summarized in a suggestion for a procedure for an enhancement of compatibility of the vehicle fleet that could lead to a European standard.

Principal items of compatibility are vehicle mass, vehicle stiffness, lateral fork effect, vertical fork effect, low/high front end of vehicles in frontal impact, high front end of the striking vehicle in side impact, longitudinal engine, transverse engine, a well-balanced distribution of the force in the front end and other effects to be derived from accident analysis.

A consortium of a sufficient number of manufacturers representing different vehicle concepts, e.g. front-wheel or rear-wheel drive, longitudinal or transverse engine, large and small vehicles, offers good prerequisites for such an analysis. A European approach is necessary to influence the behavior of as many vehicles as possible. Compatibility is not so

much a characteristic of a single vehicle, but rather that of a vehicle fleet. Previous theoretical approaches showed that an increase in compatibility in the vehicle fleet will lead to a significant decrease of fatalities and injuries in vehicle accidents. French estimations find 675 fatalities avoided and 12850 severe injuries avoided annually in the EU. Cooperation with other institutions interested in this research is therefore desirable and is being actively sought, because of the relevance of the project to European and probably worldwide regulation.

The project defines the steps to deal with compatibility. Regarding results, it remains open, because these should depend on the accident analysis, crash tests and crash computer simulations performed within the scope of this project. It is not easy, to preserve this degree of freedom for such a scientific project, because there is a great deal of political pressure for a quick solution.

For other compatibility projects compare Faerber, 1997, Hobbs, 1996, Klanner, 1998.

Activities of a car manufacturer to enhance fleet compatibility are described by Schoeneburg, 1996 and 1998.

### *Conclusion*

Compatibility research must deal simultaneously with self protection as well as with partner protection. Otherwise, there is the danger that self protection will be reduced by the attempt to achieve higher levels of partner protection. Car-to-car accidents predominate as far as all injuries are concerned. Single vehicle accidents predominate as far as fatalities are concerned.

Not all compatibility features that are theoretically valid, are valid in terms of injury reduction. Dominating everything is the influence of mass. All other influencing factors are of minor importance. Nevertheless, there is a tendency that higher longitudinal frame members may even provide lower levels of self protection. They may even also provide lower partner protection in side impacts. Higher sill height may offer more self protection in side impacts, but all of these results were obtained from German accident data and must still be verified by other European data sets.

Stiffness and the amount of deformation of a vehicle in a crash is not a significant influencing



factor. It is surprising that the influence of stiffness is so difficult to detect.

When two vehicles collide, and if their closing velocity is less than their doubled design speed, then there is sufficient deformation energy available for this particular crash. This holds, regardless of the mass-ratio between the two vehicles.

As a consequence, the small vehicle should be able to force the large vehicle to deform. This can be assured if the designer of the small vehicle knows the force level that is required to force the large vehicle to deform. A maximum force must be defined for this purpose. The bulkhead concept means that the compartment of the small vehicle is protected by a "bulkhead" in such a way that it cannot collapse as long as the other vehicle is still deforming, and as long as the maximum force level is not exceeded.

This bulkhead concept has certain limitations. The higher the level of self protection is defined, the higher this maximum force level must be. This means that deceleration in the small vehicle is high. Current restraint systems are able to protect the occupant up to a certain degree of compartment deceleration. If one takes into account this conflict of demands the context of a current barrier impact speed of 56 km/h only up to a mass ratio of 1.6, this bulkhead concept remains valid. However, this will already cover 90% of mass ratios occurring in Germany in car-to-car accidents.

A short-term compatibility test has been defined by VDA, the German Automobile Industry Association. A compatibility project, funded by the European Commission was commenced at the beginning of this year. Nearly all European manufacturers are participating. Its recommendations on compatibility evaluation is expected in 2000.

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# DEVELOPMENT OF A NEW CRASH-CUSHION CONCEPT FOR COMPATIBILITY PURPOSES OF RIGID OBSTACLES NEAR THE ROAD

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## ABSTRACT

This paper describes the development of a new, easy to handle and economic crash cushion for rigid obstacles to reduce occupant loads and injury risk during the impact.

Out of different concepts and experimental crash tests of energy absorbing barriers a mixture of concrete and granulated plastics ('Styroporbeton') has led to the best results regarding car deceleration and intrusions.

The improvement of occupant safety of this system is documented on the one side by comparing car deformation and acceleration behavior of crash tests with and without a crash cushion in front of a rigid barrier and on the other side by comparing the impact velocities of crash tests with and without crash cushion, causing similar car deformation.

For instance the car deformation of a 95 km/h crash against the crash cushion can be compared with a crash against a rigid barrier with an impact velocity of 52 kph.

## GENERAL

There is an increasing demand for mobility within the whole world. The number of vehicle registrations is growing, producing greater traffic densities. However, there has not been a corresponding increase in the available traffic infrastructure. This introduces major problems for the society. Greater mobility will reduce traffic safety if there are no safety improvement strategies to address the changing traffic situation.

The confined traffic space and the narrowness of obstacles or danger zones near the road are responsible for many accidents and injuries. Annually, many people suffer from injuries due to a crash into these objects. Enormous economic and societal costs for the society are produced by this accident type. Therefore, the development and mounting of crash barriers was a logical step.

Active (primary) and passive (secondary) safety are two different aspects in traffic safety, whereby the active safety contains measures to avoid accidents and the passive safety contains the token measures to reduce the accident severity. Although great efforts and improvements in active safety have been achieved many accidents caused by different circumstances occur. Current compatibility research and development are mainly focused on car to car and car to truck crashes. A significant part of accidents with severe and fatal injuries of the occupants results from car collisions against rigid obstacles (like tunnel portals) near the road with impact speeds on a relative high level which are often higher as the specified crash test standards and therefore intrusions and high acceleration forces endanger the occupants.

Usually car structures are optimized to fit the safety standard (crash tests) for occupants. If the energy from high velocity impact can be reduced to levels similar the standard crash tests by energy absorbing objects around rigid obstacles the injury risk will decrease.

The ideal solution for safe road conditions is to remove all barriers near the road and to provide enough space to decelerate a vehicle in dangerous situations. But this is an impractical request and therefore the most effective method is an adequate design of obstacles in such a way that barriers also dissipate energy.

Optimal conditions could be achieved by absorbing energy not only by the car structure as also by an energy absorbing cushion in a way, that intrusions to the passenger safety cell are avoided as well as the acceleration pulse is on a tolerable level.

The loads to the vehicle occupants during a crash depends on the mass of the occupant and the decelerations affecting this mass. The deceleration depends on the velocity change, the deformation distance and the restraint system of the occupants. The masses of the occupants and the change of velocity or the impact velocity are given values and so the only parameter to influence the occupants safety is the distance for the velocity change. This is on the one hand the deformation

distance and on the other hand the possible movement of occupants, provided by the restraint system.

There is a clear correlation between deceleration and deformation distance. If the impact is totally plastic the deceleration depends only on the deformation distance (for a given impact velocity), but the structural load is proportional to the vehicle mass.

The crash configuration is optimal if the kinetic energy is dissipated by the deformation of the vehicle's front and no intrusion into the passenger compartment occurs.

Typical values for the crash against a rigid wall are: about 25% of the kinetic energy dissipated by the deformation of one longitudinal beam and 50% by the displacement of the engine. If there is no rigid barrier the frontal parts of the vehicle can not deform optimal and therefore other parts of the vehicle are loaded. Accident investigations have shown that there is a higher risk to be injured by intrusions than by accelerations or belt loads. Therefore the main goal should be to avoid intrusions into the passenger compartment.

The acceleration loads increase with increasing overlap, in opposite the possibility of intrusions increase with decreasing overlap (caused by the increasing deformation).

By means of crash cushions the deformation distance will increase and the deceleration will be reduced. Because the vehicles are optimized for different crash tests (especially the frontal impact against a rigid barrier with an impact velocity higher than 50 kph) the restraint systems are designed for such crashes. If the use of crash cushions leads to similar occupant loads the injury risk for the occupants will be reduced.

## METHODOLOGY

In a first step different materials and concepts were tested on a crash sled. Out of this experiments different crash cushions were designed and tested in a crash facility designed for such tests under similar crash conditions. The crash vehicles were accelerated towards a concrete block with a mass of 24.000 kg, using two fixed pretensioned ropes for leading the crash car and a towing rope for the acceleration. Few meters before the barrier the vehicle and the ropes were released by a special mechanism and the car crashed without external influence against the cushion, which was fixed in front of the concrete block (Figure 1.).

The longitudinal and lateral accelerations of the cars during the impact were measured by means of an accident data recorder (UDS™ Unfalldatenspeicher by VDO-Kienzle®) fitted in the trunk of the vehicle. The

crashes were also documented with a high speed video camera using a frame rate of 1000 pictures per second. After the impact the vehicle deformations were documented with detailed photos and measurements.

Also simulations for the estimation of the occupant loads using the MADYMO (MATHematical DYNAMIC MOdel; multibody and FEM computer package) tool of PC-CRASH (program for the simulation of motor vehicle accidents) were executed.

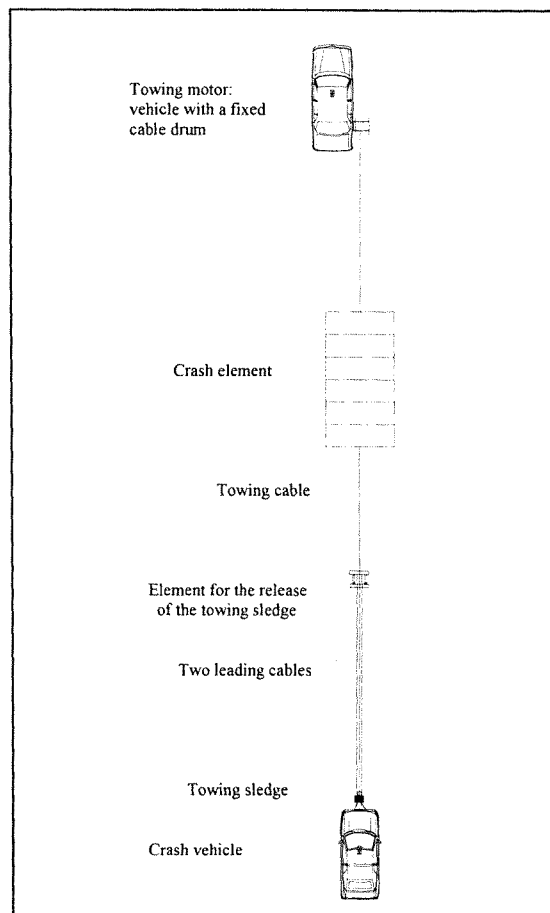


Figure 1. Crash Facility.

## CASE 1: TMA

The first crash was a Ford Escort against a so called TMA-element (Truck Mounted Attenuator) from Energy Absorption Systems, Inc., a construction which was designed to reduce severity of collisions with work vehicles. It consists of a Durashell Nose for low speed impacts and an aluminum construction for dissipating energy by impacts on higher speed levels. This element is used in some countries and the effectiveness has been proofed. The dimension of the tested TMA was 2,21 x

2,39 x 0,66 [m] and it was fixed 0,2 m above the ground (see Figure 2).

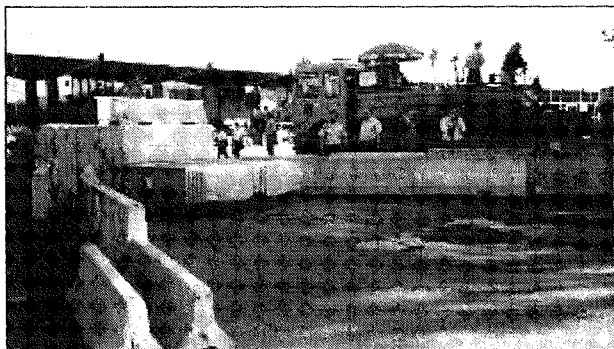


Figure 2. TMA.

The impact velocity was 89 kph, the angle of impact was  $0^\circ$  with 100% overlap. The mean deceleration during a crash time of 200 ms was  $136 \text{ m/s}^2$  with a maximum of 29 g. There were no intrusions into the passenger compartment and the doors opened without restriction. The pedals were displaced minor, the deformations of the vehicle front reached the front axle, the base plate, the A-pillar and the top were not damaged.

The deceleration diagram (see Appendix) shows two peak values, the first 20 ms after the impact when the engine hits the element and the second peak value occurs after 80 ms when the wheels come into contact with the car-body. The elastic part of the crash is minor, remarkable is the break of the whole vehicle front into the cushion without major deformation.

## CASE 2: STYRODUR

Crash against an element consisting of 25 pasted plates of Styrodur and a 2 mm sheet-metal at the front.

The element was installed 0,20 m above the ground (dimension  $1,02 \times 1,88 \times 0,60$  [m]) and impacted by a Ford Escort with 100% overlap and an impact speed of 89 kph, the angle of impact was  $0^\circ$ . The mean deceleration during ca. 100 ms was  $171 \text{ m/s}^2$  with a peak value of 33 g (see Appendix).

The passenger compartment was damaged, the dashboard twisted, the base-plate deformed and the seats had an inclination to the front, the pedals were displaced into the foot room, the steering wheel displaced vertical. The car-body had immense deformations and the roof had a dent near the B-pillar.

15 ms after the impact the engine hood started to deform, after 35 ms the wheels reached the barrier and the first cracking occurred, 50 ms after the impact the

elements disintegrated and the vehicle had large deformations. The front axle went back and 60 ms after the impact the axis reached the A-pillar, the element was smashed and the windshield was dropped, the rear axle lost the contact to the ground. The vehicle went up about  $40^\circ$  and rotated left (about  $15^\circ$ ), after 950 ms it stood still.

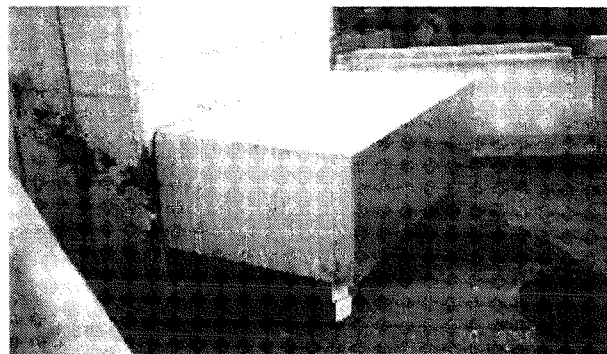


Figure 3. Styrodur-element.

## CASE 3: TIRE PILE



Figure 4. Tire pile.

The crash element contained tires which were stored in metal barrels (see Figure 4.). The element with the dimension  $1,70 \times 1,15 \times 1,05$  [m] was impacted by a Ford Escort with an impact speed of 93 km/h and 100% overlap. The mean deceleration was  $125 \text{ m/s}^2$ , the peak value about 35g. The deceleration pulse showed three sections with peak values after 20, 50 and 110 ms (see Appendix).

The passenger cell was deformed, the base plate buckled slightly and therefore the seats inclined. The firewall also showed deformations, the pedals and the steering wheel were displaced, the roof had a small dent near the B-pillar and the front door could not be opened.

15 ms after the impact the hood deformed and the first barrel was destroyed. After 90 ms the vehicle

reached the wall behind the barrel element and therefore immense deformations appeared, the front axle was brought to the A-pillar, the wind screen dropped. The rest position of the vehicle was 1,5 m in front of the crashed barrier.

#### CASE 4: HONEYCOMB STRUCTURE

This element was built of 0,36 mm tinplate, which was buckled and welded to a honeycomb structure (see Figure 5.).

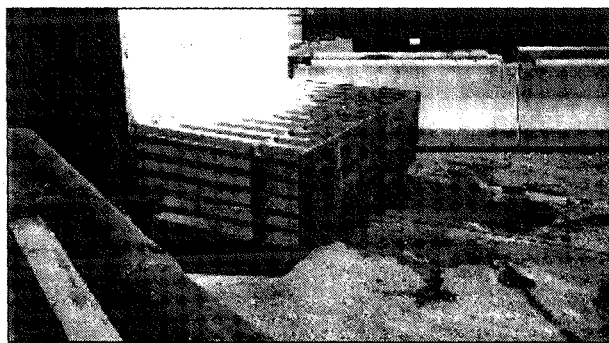


Figure 5. Honeycomb-element.

On the front a 4mm sheet-metal was fixed. The element was installed 0,20 m above the ground (dimension 1,10 x 2,08 x 0,59 [m]) and impacted by a Ford Escort with an impact speed of 88 km/h with 100% overlap. The mean deceleration during 120 ms was 229 m/s<sup>2</sup> with a peak value of 43 g (see Appendix).

There were immense deformations into the passenger compartment, the A-pillar was cracked, the base plate deformed, the pedals and the steering wheel were displaced into the passenger cell. The roof was deformed on a wide area and the front axle went back to the A-pillar. The opening of the front doors was impossible.

30 ms after the impact the tires contacted the crash element, the first part of the cushion deformed with fold bumps, but this effect ended and the vehicle deformed. The front axle and the front structure had extensive deformations, after 80 ms the vehicle was damaged and the rear axle went up.

#### CASE 5: EEVC

The crash element was built out of two EEVC (European Experimental Vehicle Committee) side impact elements built by the company Fritzmeier. This element is used for side impact crash tests in Europe. It consists of 6 PU-foam pieces with defined properties and a sheet-metal in front (see Figure 6.).

The element (dimension 0,94 x 1,50 x 0,50 [m]) was impacted by a Ford Escort with an impact speed of 80 km/h. The mean deceleration was 166 m/s<sup>2</sup> with a peak value of 32 g (see Appendix).

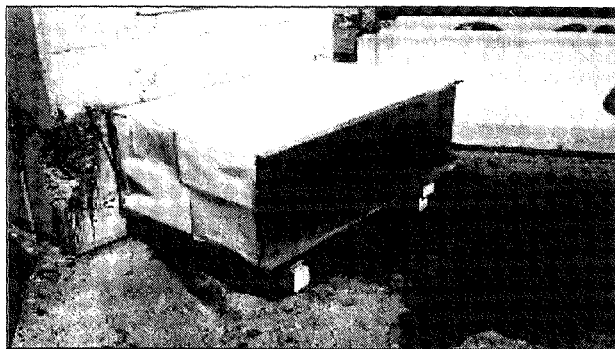


Figure 6. EEVC-element.

The steering wheel and the pedals were displaced, the dashboard twisted, also the base plate was deformed and the seats had a frontal inclination. A dent on the roof near the B-pillar and front axle deformations could be observed and the front door opened only by large forces.

The first element was deformed without remarkable vehicle damage but when the second part of the element was reached after 50 ms the front axle contacted with the car-body and the vehicle deformed.

#### CASE 6: 'Styroporbeton'

A mixture of concrete and granulated plastic (Protteolith®) was used for this element (see Figure 7.).

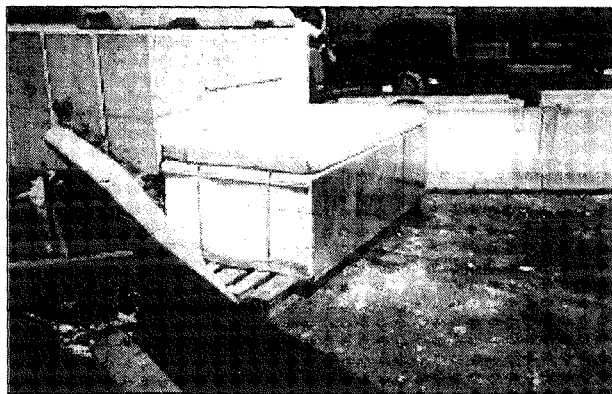


Figure 7. 'Styroporbeton'-element.

The element was installed 0,20 m above the ground (dimension 1,00 x 2,00 x 0,60 [m]) and impacted by a Ford Escort with an impact speed of 80 km/h and 100% overlap. The mean deceleration during 120 ms was 187 m/s<sup>2</sup> with a peak value of 31 g (see Appendix).

During the first 20 ms no vehicle deformation could be observed, after that time the tires contacted with the element, the vehicle burst into the element and 90 ms after the first contact the element was demolished.

The passenger cell was not destroyed remarkably, the roof, the base plate and the seats were deformed minor, the firewall was without deformation and the front axle went back.

#### CASE 7: RIGID WALL

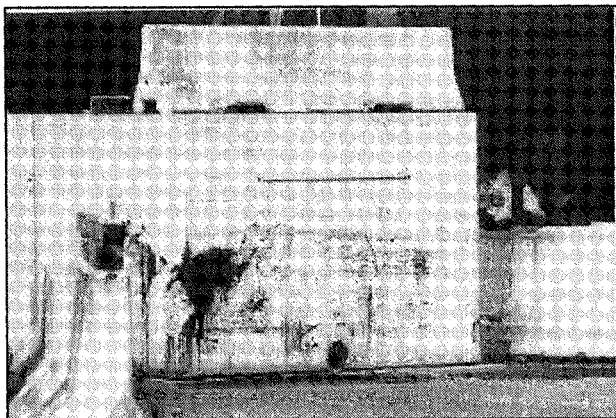


Figure 8. Rigid wall.

Crash against the concrete block with a impact speed of 89 km/h and 100% overlap. The mean deceleration during 120 ms was  $217 \text{ m/s}^2$  with a peak value of 43 g.

The whole passenger compartment was destroyed, the pedals contacted with the seat and the headrests contacted with the roof. The dashboard, the base plate, the firewall, the roof and the A-pillar were damaged extremely.

#### FINDINGS OF THE FIRST TESTING SERIES

The best results were shown by the TMA barrier and by the 'Styroporbeton'-element, also the tire-element brought acceptable results but modifications to this element would have been too complicated. Therefore the decision was made to optimize the 'Styroporbeton'-element because of the great potential which could be seen in the first test series.

- easy to handle
- inflammable
- lower costs
- recycled material and the possibility to recycle the element after the impact
- flexibility

For the next series the element was modified regarding dimensions and structure. The length of the

element was enlarged to 1,60 m, the mixture rate of the 'Styroporbeton' was changed and different densities were combined to test the effect of different mixtures and to get to a progressive force trend. Also an offset crash with a high impact speed was done.

- case 8:  $1,80 \times 0,80 \times 1,60 \text{ [m]}$ , two pieces ( $1,80 \times 0,80 \times 0,80 \text{ [m]}$ ) with different densities ( $170 \text{ kg/m}^3$  and  $280 \text{ kg/m}^3$ ) combined to one element.
- case 9:  $1,80 \times 0,80 \times 1,60 \text{ [m]}$ , with constant density ( $190 \text{ kg/m}^3$ ).
- case 10:  $1,80 \times 0,80 \times 1,60 \text{ [m]}$ , two densities combined. ( $190 \text{ kg/m}^3$  and  $330 \text{ kg/m}^3$ )

#### CASE 8: STYROPORBETON (170/280)

The element was installed 0,20 m above the ground (dimension  $1,80 \times 0,80 \times 1,60 \text{ [m]}$ ) and impacted by a Ford Escort with an impact speed of 81 kph and 100% overlap. The middle deceleration was  $168 \text{ m/s}^2$  during a period of 140 ms, with a maximum value of 30 g (see Appendix).

The vehicle front was shortened approx. 20 cm, the deformations reached up to the a-column. The wheel base left was shortened around 9 cm and on the right around 15 cm. The passenger space remained intact, the injury risk for the occupants depends mainly on the acceleration load.



Figure 9. Vehicles after the impact against the rigid barrier with 83 kph (left) and impact against the 'Styroporbeton' cushion with 81 kph.

#### CASE 9: STYROPORBETON (190/190)

A Ford Escort crashed with 94,5 kph with 100% overlap against the barrier with a homogeneous density. The deceleration during a time of 195 ms was  $136 \text{ m/s}^2$  with a maximum value of 28 g (see Appendix). The frontal part of the vehicle was deformed approx. 30 cm.

The front axle shifted 10 cm to the rear. The passenger space was intact, the injury risk is given by the acceleration load.

#### **CASE 10: STYROPORBETON (190/330)**

Crash against an element with two different qualities of 'Styroporbeton' with an impact speed of 97 kph and 50% overlap.

The impacted barrier was deformed on the subjected side completely, the other side remained almost undeformed. After the barrier was used up, the rear of the vehicle rose highly, the vehicle made a 90° counter clockwise rotation and came approx. 1 m to the right and 1,5 m to the rear to the deadlock. On the impacted side of the vehicle it came to substantial deformations. The left side of the vehicle was destroyed up to the A-pillar. The driver's door was blocked after the crash, the roof was warped. The passenger compartment was reduced, the steering wheel and the pedals were shifted inward. The front of the vehicle was bent to the left and the frontal axle was shifted about 54 cm to the rear on the driver's side. On the other side the distance between front and rear wheel became larger.

The main danger for the occupants might result from the intrusions and not only from the acceleration loads.

#### **CONCLUSION**

Both elements which were crashed with 100% overlap brought good results but the second part of the 1. element was too stiff. The deformation of the vehicles is similar to the deformation of a crash against a rigid concrete barrier with 40 to 50 kph. There are no intrusions into the passenger safety cell and therefore only the acceleration load is important for the occupant safety and this load can be handled by a modern safety system.

The offset-crash with 50% overlap brought intrusions but the acceleration load is on a lower level because the deformation distance is larger. Such kind of impacts are a great problem for all automobile producers and only an adequate structure and vehicle design can reduce this problems.

The 'Styroporbeton' element was designed harder than the TMA-element for a better utilization of the limited traffic space. So the vehicle front also deforms and the deformation distance for dissipating the energy can be reduced (see Figure 10.).

For the computer simulations the measured vehicle accelerations were brought to a vehicle model in which a

dummy model was placed on the front-seat passenger side (see Figure 12.). Because of the different element dimensions a direct comparison is problematic but the values shows the tendencies of the passenger load. But the intrusions into the passenger compartment are not calculated and therefore for example the tyre pile shows relative low passenger loads but during the tests intrusions into the safety cell occurred and therefore the risk for the occupants will be higher than the 'Styroporbeton' impact (see Figure 11.).

#### **ACKNOWLEDGEMENT**

The authors wish to acknowledge the funding and support from the Styrian government of this study.

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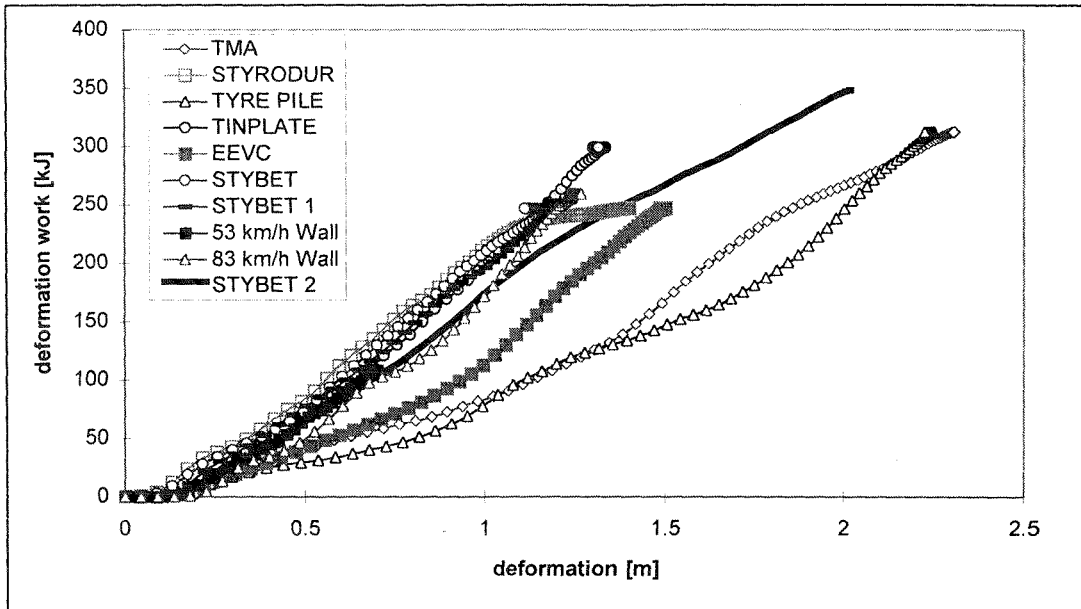


Figure 10. Deformation work and dynamic deformation for different elements

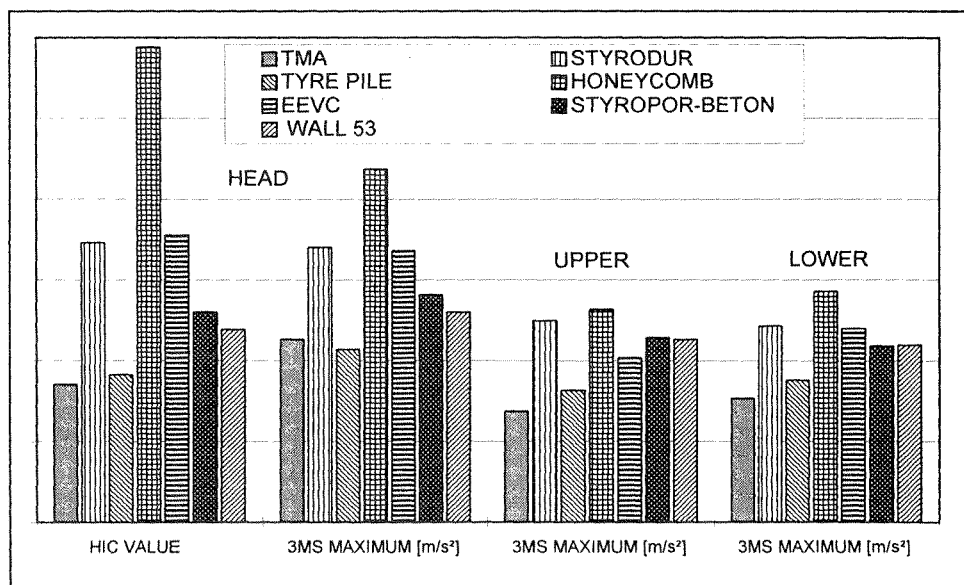


Figure 11. Comparison of injury parameters calculation for passenger side

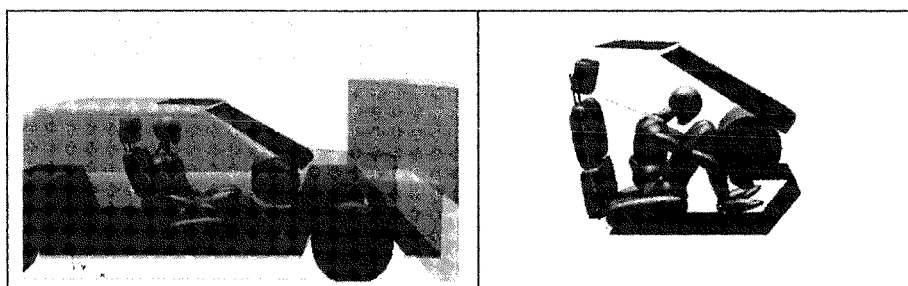
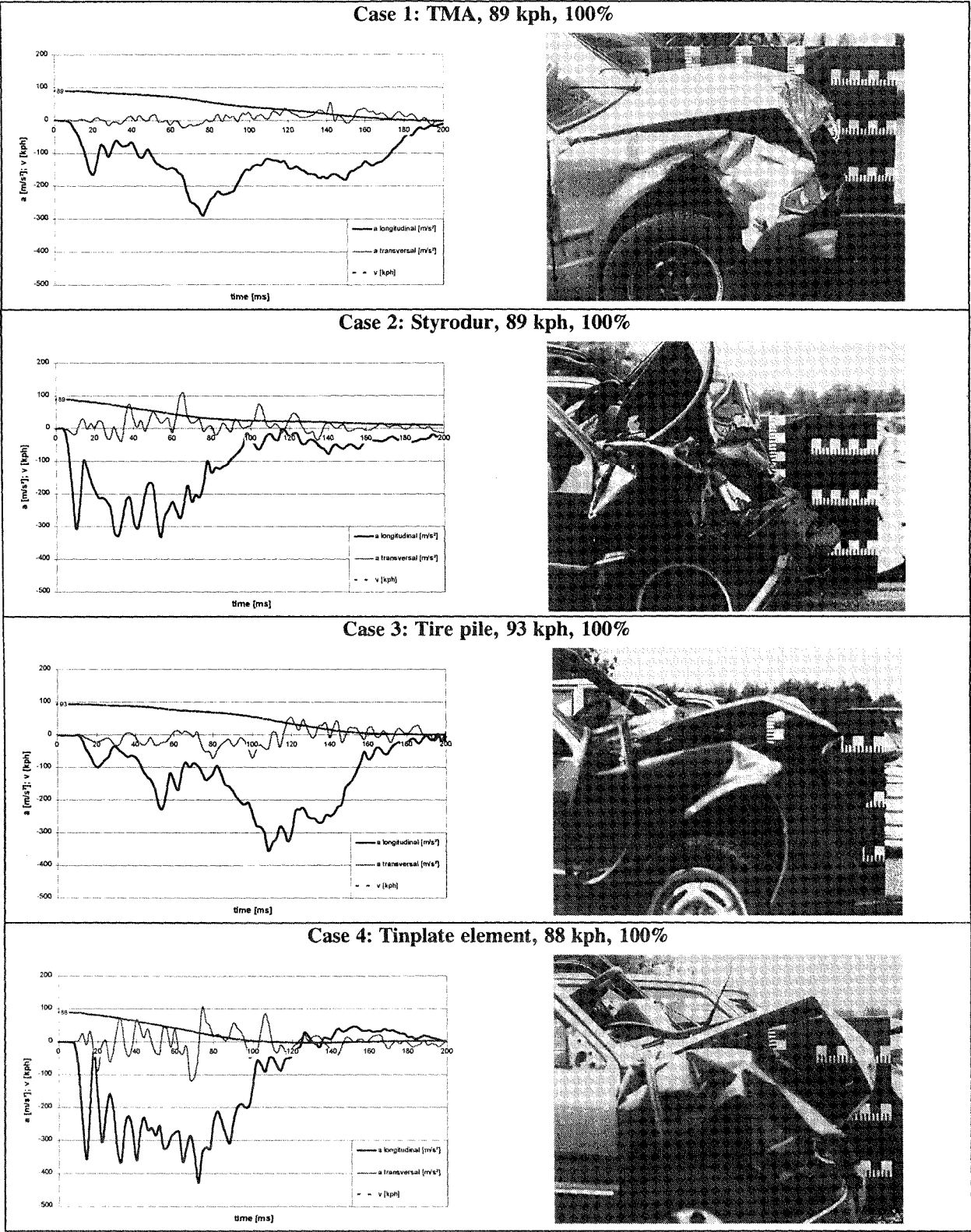


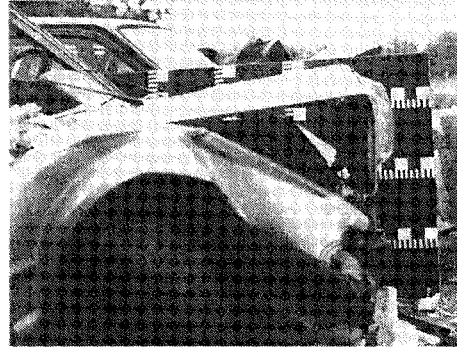
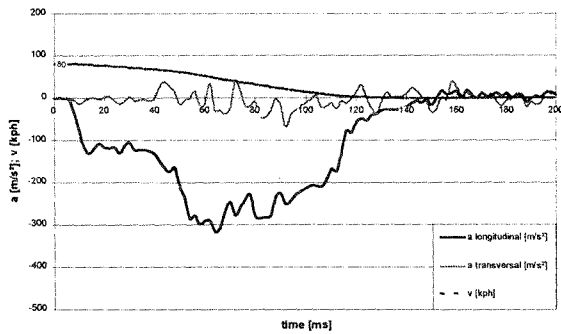
Figure 12. Model for simulation



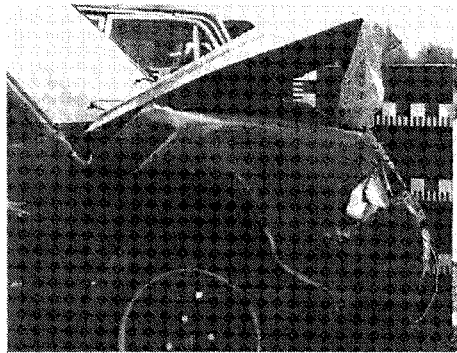
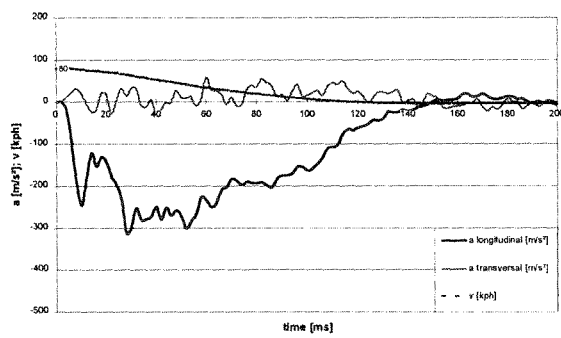
APPENDIX



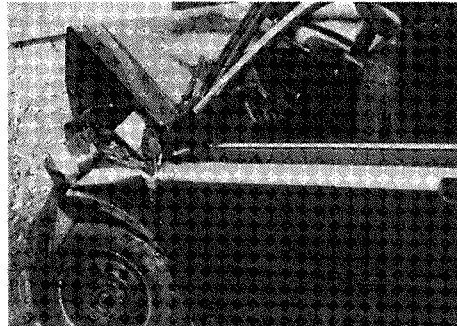
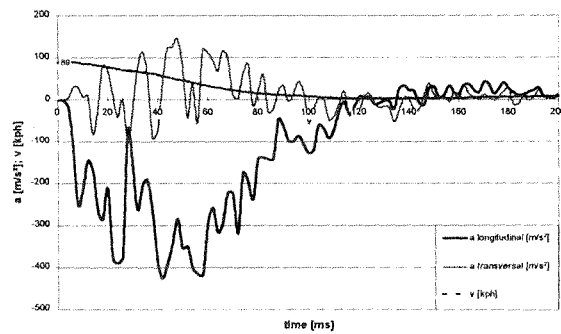
Case 5: EEVC, 80 kph, 100%



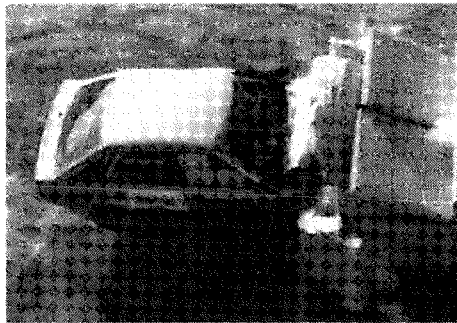
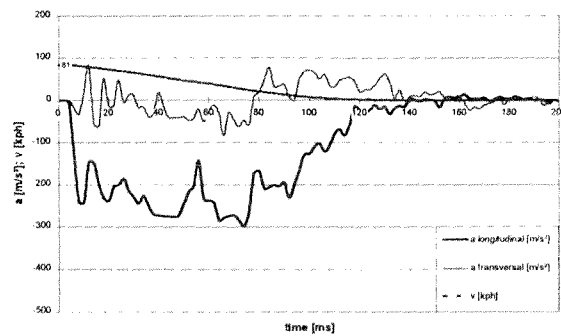
Case 6: 'Styroporbeton', 80 kph, 100%



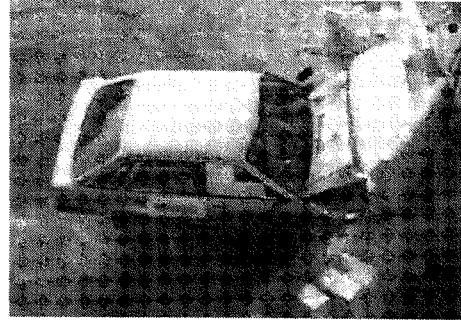
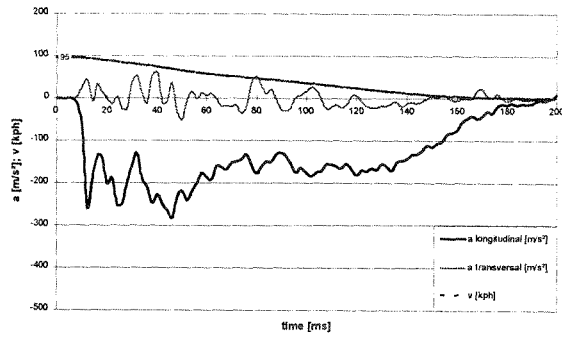
Case 7: rigid wall, 89 kph, 100%



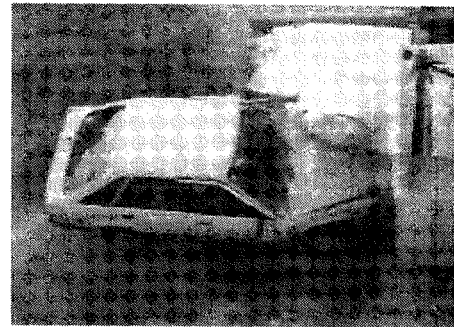
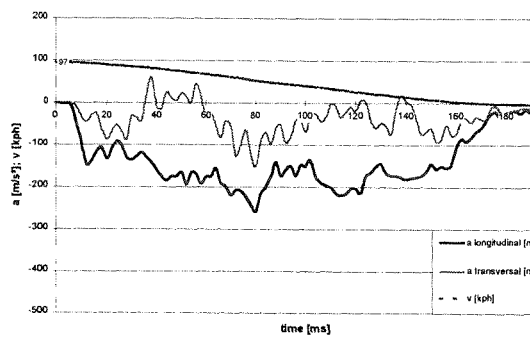
Case 8: Styroporbeton, 81 kph, 100%



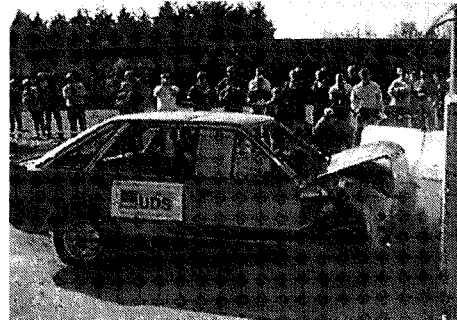
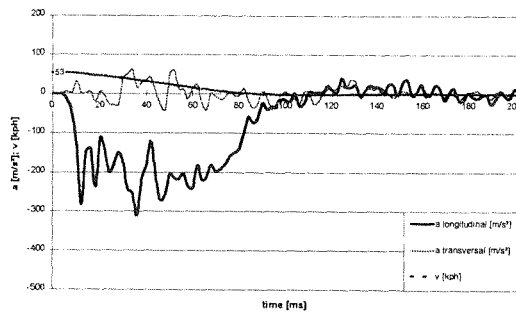
### Case 9: Styroporbeton, 95 kph, 100%



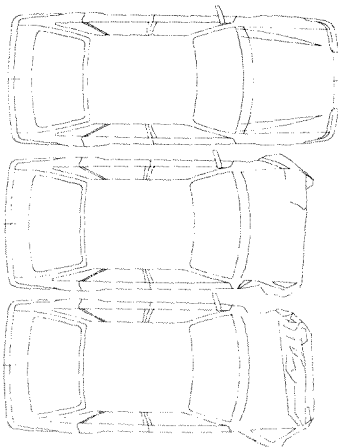
### Case 10: Styroporbeton, 97 kph, 50%



### Case 11: rigid wall, 52 kph, 100%



### Compared deformations



Ford Escort: original state

Ford Escort: 52 kph rigid wall impact

Ford Escort: 95 kph 'Styroporbeton' impact

## COMPARISON OF 10 TO 100 KM/H RIGID BARRIER IMPACTS

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Paper Number 98-S3-P-12

### ABSTRACT

Different methods and theories were developed to describe the accident severity. For accident reconstruction the EES (Energy Equivalent Speed)-method [1] is an important tool.

$$E_{\text{def}} = \frac{1}{2} \cdot m \cdot (\text{EES})^2 \quad (1.)$$

This means that the plastic deformation energy of the damaged car is expressed as a kinetic energy of the car with the virtual velocity value EES.

For an authentic EES-estimation various crash-tests with different conditions are necessary, because the energy absorption depends on various parameters. Documented car deformations for EES values up to approximately 60 km/h are available from crash tests. For higher impact velocities only very little data is published.

To gain a better understanding of the crush behavior at higher impact speeds, a series of full scale rigid barrier impacts were performed at impact speeds in the range of 10 to 100 km/h

### INTRODUCTION

For accident reconstruction and for accident research the engineers need tools for a realistic assumption of the accident circumstances. But in most of the cases there are not enough data for a reliable statement of the crash, especially the crash severity and the relationship between the crash severity and the occupant load is a difficult and controversial problem. One of the methods with the best results is the EES (Energy Equivalent Speed)-method, which was introduced and published by Burg and Zeidler [1] in 1980.

To get an appropriate estimation of the deformation energy under different crash velocities six vehicles were accelerated towards a concrete block with a mass of

about 24.000 kg, using two fixed pretensioned ropes for leading the crash car and a towing rope for the acceleration. Few meters in front of the barrier the vehicle and the ropes were released by a special element and the car crashed without external influence against the barrier (Figure 1.).

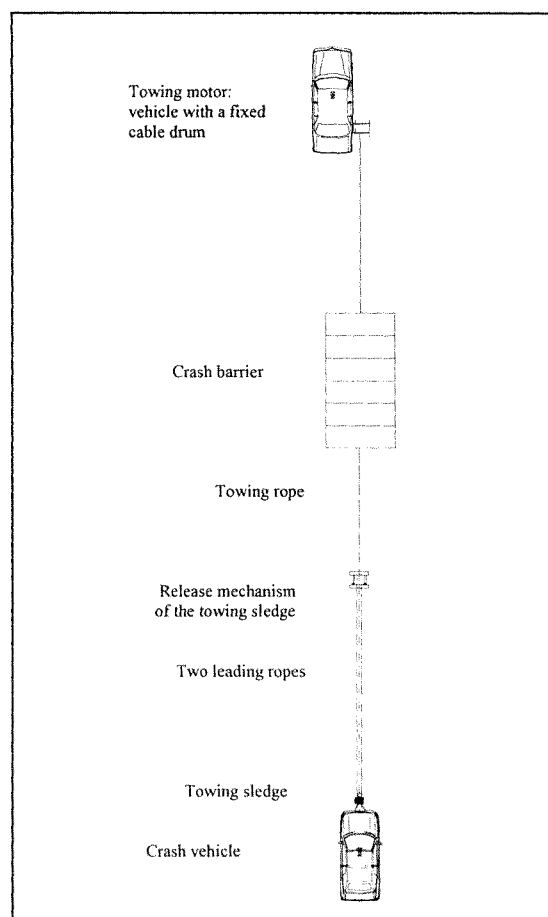


Figure 1. Crash Facility.

The longitudinal and lateral accelerations of the cars during the impact were measured by means of an accident data recorder (UDS™ Unfalldatenspeicher from VDO-Kienzle®) fitted in the trunk of the vehicle. The

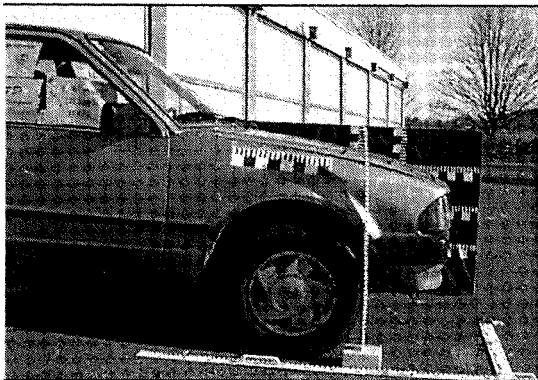
crashes also were documented with a high speed video camera using a frame rate of 1000 pictures per second. After the impact the vehicle deformations were documented with detailed photos and measurements.

On the one side frontal impacts were performed with identical cars (Ford Escort) at six different impact velocities ( 13, 21, 38, 52, 83 and 95 km/h). On the other side different cars were crashed at speeds around 90 km/h to see the influence of the car type. These results are not presented in this paper.

#### **CASE 1: 100%, 13 km/h**

A Ford Escort was crashed with 100% overlap against a rigid barrier. The impact velocity was 13km/h, the mean deceleration during the time of 60ms was about 8g with a peak value of 20g. During this test two volunteers were sitting in the car, restraint by three point seatbelts and both were without any complaint after the crash.

The remaining deformation was less than 5 cm. Only the bumper showed deformation and the hood buckled very slight (Figure 2.). The impact had an evident elastic part but the occupant load can be tolerated.

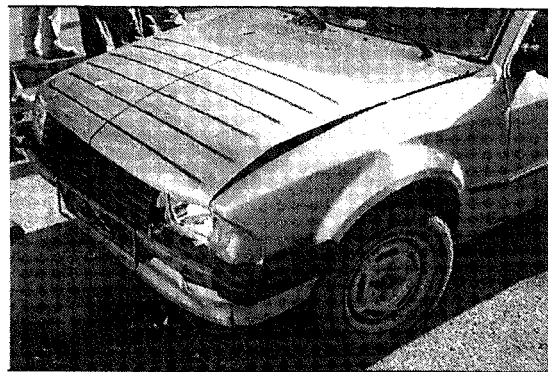


**Figure 2. Vehicle after 13km/h frontal crash.**

#### **CASE 2: 100%, 21 km/h**

The Ford Escort impacted the rigid barrier with a velocity of 21km/h and with a small impact angle of less than 5°. The mean deceleration was 6g during 100ms, the maximum value was about 14g.

The remaining deformation was about 10 cm on the left and 5 cm on the right side. The deformations could be clearly seen at the bumper, hood and the fender. The left headlight was splintered. Also the distance between the front and rear axis was reduced in opposite to the first crash (Figure 3.).

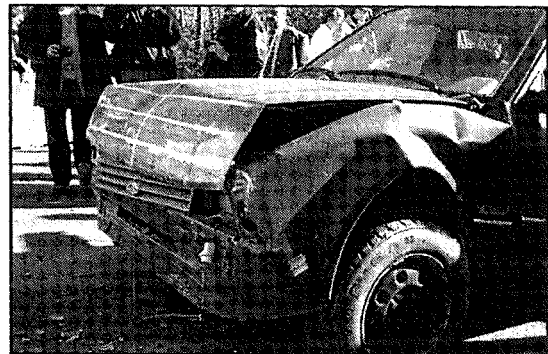


**Figure 3. Vehicle after 21km/h frontal crash.**

#### **CASE 3: 100%, 38 km/h**

The impacts velocity was 38 km/h and lead to a mean deceleration of 14g during 90ms, the maximum value was about 32g.

The remaining deformation was measured with 20 cm on both sides. Beside the buckling of hood and fenders (Figure 4.), also the distance between the front and rear axis was reduced more than 10 cm. However there were no remarkable intrusions of the passenger compartment.



**Figure 4. Vehicle after 38km/h frontal crash.**

#### **CASE 4: 100%, 52 km/h**

The Ford Escort impacts the rigid barrier with a velocity of 52 km/h, the mean deceleration is 15g during 100ms, the maximum value is about 31g.

The static deformation was about 40 cm on both sides. The bumper deformed and the hood buckled, also the fenders showed already strong deformations. The front axis moved back to the A-pillar and so the distance between the front and rear axis was reduced about 20 cm (Figure 5.).



**Figure 5. Vehicle after 52km/h frontal crash.**

Also a typical deformation on the car roof in the area of the B-pillar could be seen, which is brought through the A-pillar to the cars top.

#### **CASE 5: 100%, 83 km/h**

The Ford Escort hit the rigid barrier with a velocity of 83 km/h, the mean deceleration was 20g during 110ms, the maximum value was 42g.

For the remaining deformation 60 cm were measured on both sides. The hood as well as the fenders buckled extremely and showed great deformations. The front axis moved back to the area of the A-pillar and so the wheel-base was reduced about 40 cm. Also the doors showed deformations and there were remarkable great intrusions into the passenger compartment. Finally the base plate was wrinkled (Figure 6.).



**Figure 6. Vehicle after 83km/h frontal crash.**

#### **CASE 6: 100%, 95 km/h**

For the last case the vehicle hit the rigid barrier with a velocity of 95 km/h, the mean deceleration was more than 20g during 110ms, the maximum value was at a level of 49g.

The remaining deformation was 70 cm on both sides. The front of the vehicle had deformed extremely. also the hood had great plastic deformations. The front axis moved back behind the A-pillar and so the distance between the front and rear axis was reduced more than 40 cm. Also the doors have deformations and there are great intrusions into the passenger compartment (Figure 7.) and the base plate was wrinkled.



**Figure 7. Vehicle after 95km/h frontal crash.**

#### **SIMULATION**

For an estimation of the occupant risk computer simulations were executed using the MADYMO (MATHematical DYNAMIC Model; multibody and FEM computer package) tool of PC-CRASH (program for the simulation of motor vehicle accidents).

The intrusions into the passenger compartment are not calculated but at impact speeds higher than 50 km/h intrusions occur and the accident and injury statistics show that often these injuries are a great problem. Especially for impacts with an overlap less than 50% not the acceleration load is the problem. The vehicle front structure can not deform in a designed manner and therefore other structure parts are loaded. Therefore the vehicle deformation increases but the acceleration load for the occupants decreases.

The dummy was placed on the front-seat passenger side and the model was loaded with the measured crash tests pulses (Figure 8. and 9.).

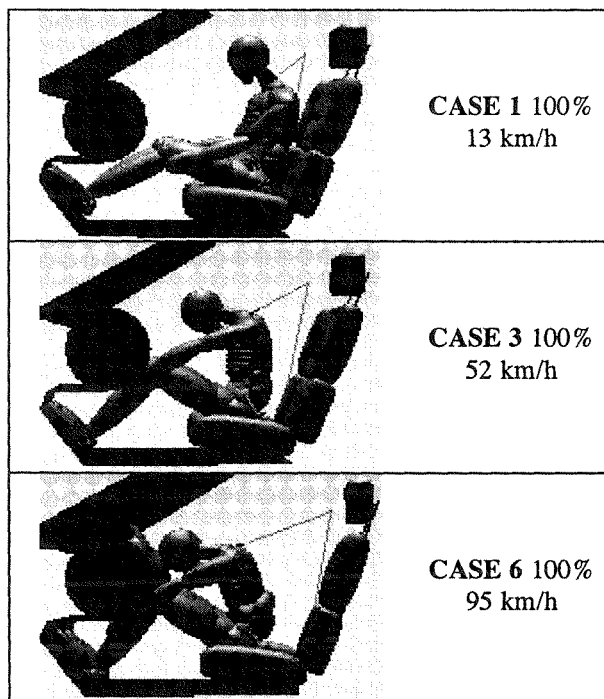


Figure 8. Simulation of maximum occupant movement without intrusions.

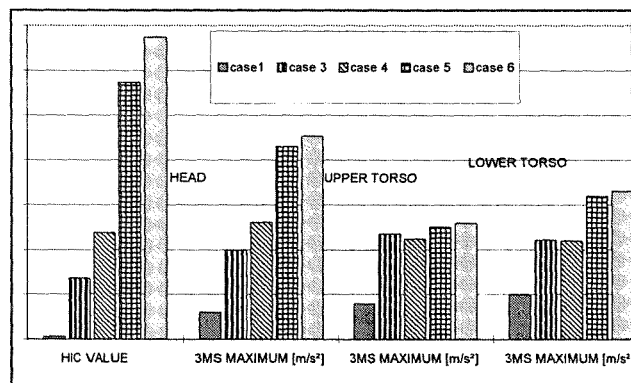


Figure 9. Comparison of injury parameters.

## CONCLUSION

As a result of the standard crash tests there are no intrusions into the safety cell at impact speeds up to 50 km/h. Because of the 100% overlap all frontal parts of the car are loaded and therefore the crash energy is dissipated in a planned way. At speed range higher than 50 km/h the frontal structure of the vehicle is overloaded and therefore also the base-plate and parts of the interior are exposed to large deformation.

The risk for the passenger safety up to the 50 km/h impact are the acceleration forces and this loads are requirements for the restraint system. Crashes with

higher impact speed result in intrusions and only new structure and compatibility concepts are able to minor this problem.

The crash test also showed a good correlation between impact speed and distance of the vehicle axes from 20 up to 80 km/h (Figure 11.).

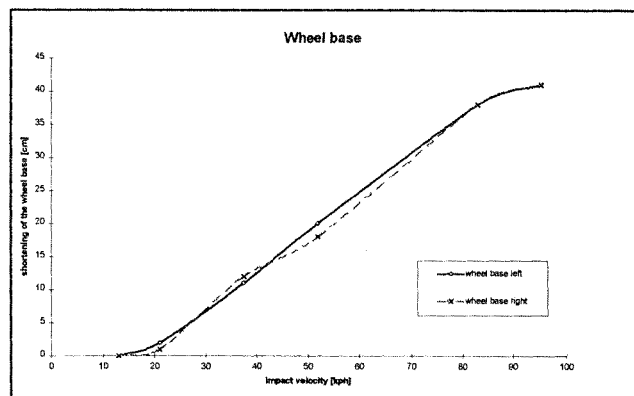


Figure 10. Relationship between impact speed and wheel base.

Table 1 Main data of crash tests

#	v [km/h]	$a_{mean}$ [m/s <sup>2</sup> ]	$a_{max}$ [m/s <sup>2</sup> ]	$\Delta v$	wheel base (l+r)/2 [cm]
1	13	78	190	15	240.0
2	21	57	137	23	238.5
3	38	144	325	42	228.5
4	52	147	310	55	221.0
5	83	198	420	84	202.0
6	95	205	490	96	199.0

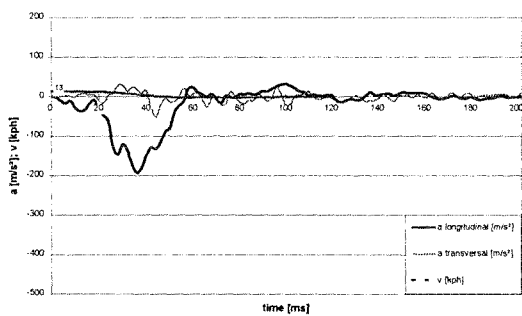
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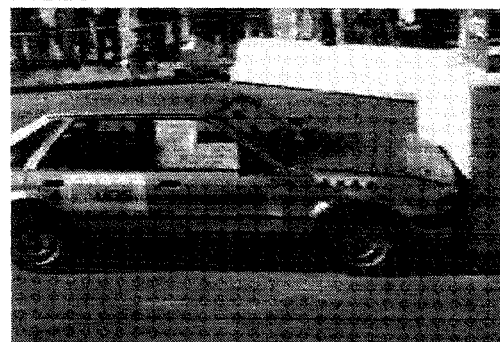
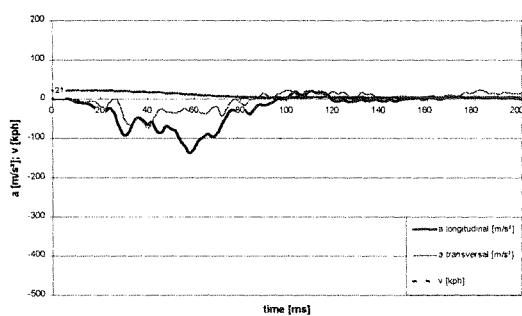


## APPENDIX

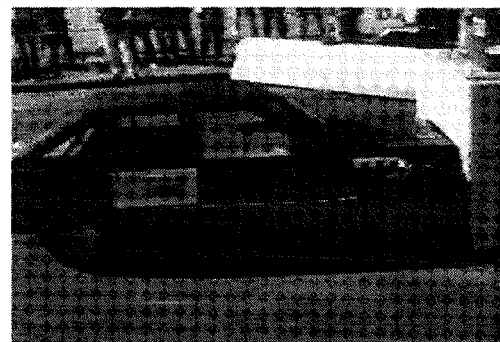
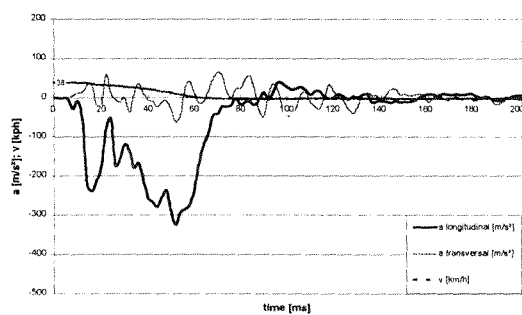
CASE 1: 100%, 13 km/h



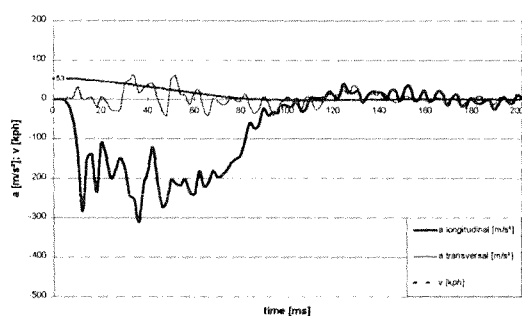
CASE 2: 100%, 21 km/h



CASE 3: 100%, 38 km/h



CASE 4: 100%, 52 km/h





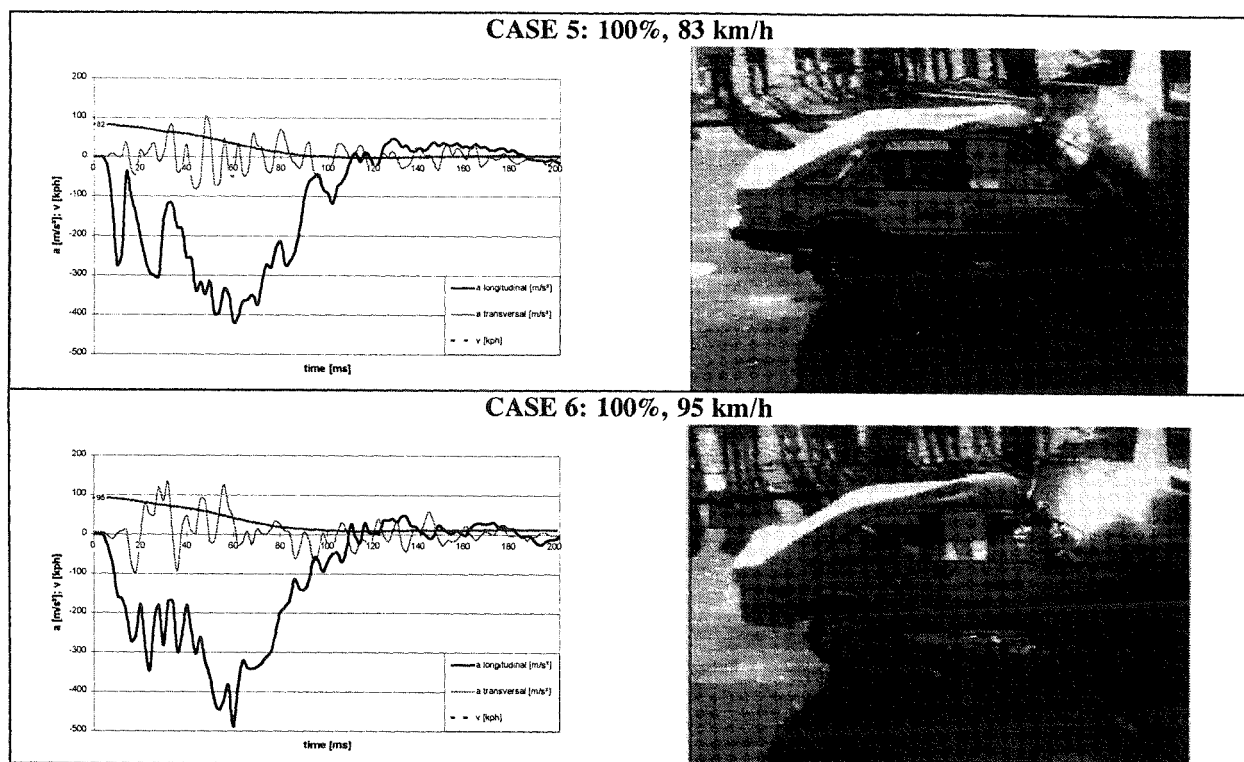


Figure 11. Car acceleration and crash conditions

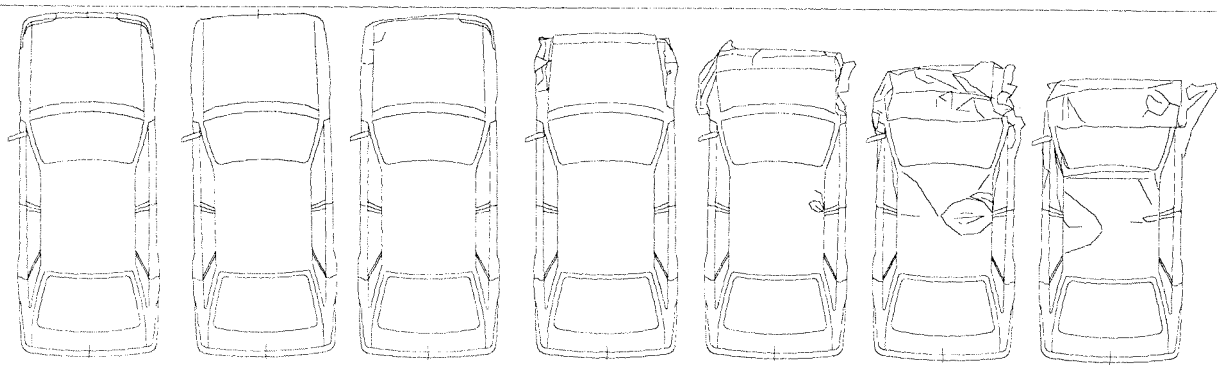
Original state	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Impact speed	13 km/h	21 km/h	38 km/h	52 km/h	83 km/h	95 km/h
						
max. Deformation [cm]						
0	< 5	10	20	40	60	70

Figure 12. Remaining car deformations

## PROGRAMMABLE DECELERATION DEVICES FOR AUTOMOTIVE TESTING

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Paper Number: 98-S3-P-13

### ABSTRACT

This paper provides an overview and analysis of a programmable deceleration device for crash pulse simulation systems. Briefly the differences between acceleration or deceleration sleds for simulation are outlined. Working principle and technical data of the device are explained. By means of test results qualities like reproducibility, repeatability, and the ability to simulate crash-pulses are presented.

### INTRODUCTION

In today's car design for passive safety sled test play a more and more important role. Since programmable systems for crash pulse simulation were introduced into the market, they proved to be a helpful tool in component testing, computer model validation, and restraint system optimization, etc.

### CRASH PULSE SIMULATION

Acceleration vs. Deceleration Devices - Impact simulation systems can be divided into two categories. The first group simulates the impact actively by accelerating a resting sled with hydraulic or pneumatic actuators. Their major advantage is that the whole system is at rest at the beginning of a test and the simulation results are excellent. Disadvantages are the high installation costs and the limitation to perform exclusively component tests on these systems.

The second category are the so-called deceleration devices. With these systems the sled moves initially with impact speed. To simulate the impact the sled intrudes a brake system. The mounted components on the sled experience a specific deceleration by controlling the brake force. Due to their compact design these systems can be mounted on full scale crash tracks, typically onto the face of the impact block. However the rear end of the track can be used either. Consequently, the major advantage of a system like this is that the same track can be used for car crashes and for sled tests as well. The simulation results obtained from either system are comparable.

Deceleration devices like the bending bar brake, spring bar brake, PU-tube brake, or the system

introduced in this paper, the HYDRO-BRAKE system, belong to the later group.

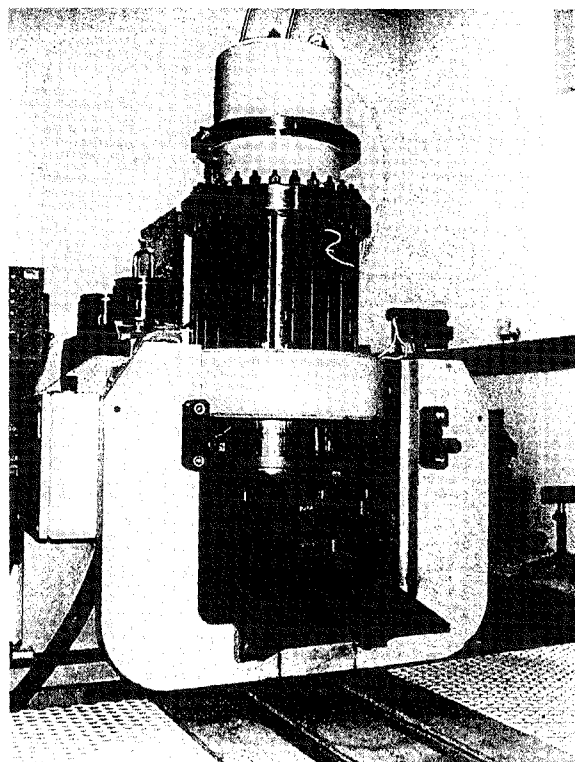


Figure 1. HYDRO-BRAKE System viewed from the front.

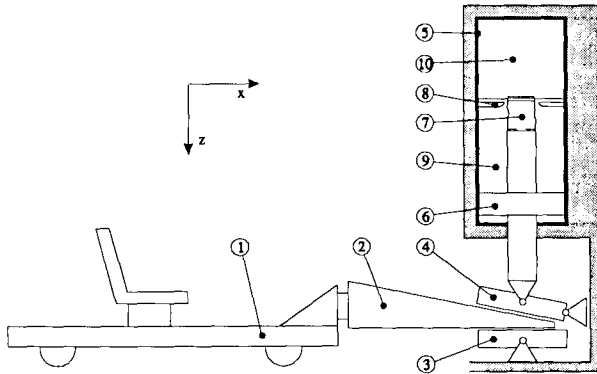
### HYDRO-BRAKE System

The HYDRO-BRAKE system (see Figure 1) which is introduced in this paper is among the deceleration devices. It is capable of simulating crash pulses

- with peaks up to 70 G ,
- sled masses up to 2,000 kg,
- pulse slopes up to  $\pm 4$  G/ms,
- impact speed up to 80 km/h,
- brake distance up to 1 m (option 1.2 m),
- and repeatability better than  $\pm 0.5$  G.

With an overall length of 1.7×1.2 m (width×height) and a total weight of 1,500 kg the HYDRO-BRAKE system is a fairly compact system and easy to handle.

**Working Principle** - In Figure 2 the HYDRO-BRAKE system is schematically shown.



**Figure 2. Operating principle of the HYDRO-BRAKE.** Shown is the test sled with the impact wedge, brake pads, hydraulic unit mounted.

The brake system comprises of two main parts. First the hydraulic system second the two brake pads (3) and (4). The lower one is stationary mounted the upper one is connected with the same angle as the impact wedge (2) to the hydraulic piston (6) which is housed in cylinder (5). At the lower end of the piston the upper brake pad is mounted and at the upper end a metering pin (7). Together with this pin a mask separates (8) two volumes (9) and (10). Initially volume (9) is filled with oil and volume (10) with air.

The impact wedge (2) connected to sled (1) intrudes with impact speed the brake system. At time  $t=0$  the impact wedge sits tightly between the two brake pads. Due to its angle the penetrating wedge is forcing the upper pad to move in Z-direction. As the wedge is moving, the piston presses oil through the gap between the metering pin and the mask. The gap size and the piston velocity in -Z-direction at any time  $t$  determines the pressure in volume (9) as the oil flows from volume (9) to (10). Depending on the contour of the metering pin it reveals a once more once less sized gap as it moves through the mask. Hence, the pressure in volume (9) changes as the metering pin reveals the gap. Due to the direct coupling of deceleration of the sled and the position of the metering pin in the mask one has a tool to determine the pressure at each instant during the deceleration process. Together with the area of the piston the pressure determines the deceleration force and consequently the time-deceleration history.

For a wanted time-deceleration curve an especially written software tool is calculating the shape of the metering pin. In order to do this the software requests the test's boundary conditions like time-deceleration curve and the sled's total mass. Subsequently the software

generates the metering pin's diameter as a function of the position on the z-axis.

One feature that makes this system work so well is the orientation of the piston in Z-direction instead in X-direction like it is usually done in competitive systems. Since the wedge (2) is working like a gearbox the piston only travels  $1/7^{\text{th}}$  of the distance the sled is moving. Consequently a fraction of the oil is merely needed to be controlled. One would expect an increase in forces coming along with the spared distance. This is not the case since a large amount of energy is absorbed between the brake pads and the impact wedge. In fact with this trick the force in Z-direction is of the same value as the impact force in X-direction. Briefly: with this orientation of the cylinder the cylinder diameter can be kept constant but be built seven times shorter as operating the cylinder in X-direction.

## TEST RESULTS

Some questions regarding the capabilities of the HYDRO-BRAKE system will be discussed below.

**Reproducibility** - When simulating a crash pulse on a sled test facility it is of particular interest how precisely a predefined deceleration curve can be re-produced by the system. This property is called reproducibility. In Figure 3 this is illustrated for the HYDRO-BRAKE system.

**Repeatability** - An important characteristic of a system that reproduces predefined time-deceleration curves well is the capability of repeating already conducted test at a later time reliably. Figure 4 shows the resulting test curves from 10 subsequent tests. Figure 4 shows the excellent repeatability. Since the HYDRO-BRAKE is controlled by a invariant mechanical system (metering pin) there are no parameters that can be altered by the user or operation. Simply changing the metering pins guarantees the same test conditions from earlier conducted tests.

**Reproducing crash pulses** - A third point of discussion is the quality how crash pulses from a real car crash can be simulated. One crucial value is the rise or fall time of the deceleration. The shown predefined curve in Figure 5 was calculated with the intention to test the system response. It can be seen that the system can not keep up with the sudden drop and rise in the acceleration curve. The maximum/minimum slope possible for the HYDRO-BRAKE are 4 G/ms. This has to be kept in mind when defining the simulation curve. Hence, the high frequencies of a crash pulse can not be simulated with this system. But an averaged curve of the time-

deceleration can still match the time-velocity curve very well.

**System Handling and Maintenance** - Since one metering pin corresponds to only one combination of time-deceleration curve and total sled mass it is usually calculated for higher sled masses than needed. To avoid tooling a new pin, additional masses are added to the sled if once the mounted components are lighter than the ones used before.

Once a test is conducted the impact wedge needs to be pulled out of the HYDRO-BRAKE. For this the upper brake pad is to be lifted pneumatically, the brake opens and the sled can be pulled back. To prepare the brake for a new test the upper brake pad is lowered and the brake is then ready for a new test. The time between two tests so can be less than 2 minutes.

To simulate a new crash pulse by means of the HYDRO-BRAKE the metering pin needs to be changed. For this the lid of volume (10) is lifted, the metering pin removed, and the new one installed. After closing the lid the system is ready for a new test. The time needed to prepare the system for a new crash pulse then is about 10 minutes.

The HYDRO-BRAKE requires very low maintenance since there is wear between the impact wedge and the brake pads only. By selecting appropriate friction partners the wear can be limited. After 250 tests the HYDRO-BRAKE system did not show any significant wear neither at the impact wedge nor at the brake pads.

## FUTURE DEVELOPMENT

One crucial limitation of this system to achieve universal operation certainly is its limited brake distance of 1 m. One possibility to extend this is the reduction of the wedge angle. Consequently the hydraulic pressure will increase and a lower deceleration peak is being simulated. To maintain the performance of the system the wedge angle could be kept constant and the hydraulic system and impact wedge had to be lengthened.

Since the oil flow through the gap is fairly low for this system MESSRING is working on a closed loop control system. By using servo hydraulic valves to

control the oil flow versus time in the system it is expected to cut down time in approaching new time-deceleration curves. In addition a better high-frequency response of the system is expected.

In Figure 4 it can be seen that there is an initial peak in the beginning of the test curve. This results from the inertia of the upper brake pad, the piston and the metering pin when accelerating them to  $1/7^{\text{th}}$  of the impact speed. To prevent this a mechanical system is introduced to accelerate these parts prior the start of simulation.

## CONCLUSION

Since a full scale crash test facility can be retrofitted with the HYDRO-BRAKE system the investment costs are significantly lower compared to acceleration devices. Through its low preparation time by using automated test preparation and very few maintenance costs it is to be considered as a very cost effective system for crash-pulse simulation and especially for quality assurance testing. It is simple in use and therefore a safe and reliable system. In addition the HYDRO-BRAKE system excels through excellent repeatability.

A disadvantage of this system is the limited high-frequency response. Due to tooling times for the metering pin the time passes by to generate a complete new time-deceleration curve for this system is longer than using servo hydraulic acceleration systems. By introducing servo hydraulic valves to the deceleration device the system performance might be enhanced dramatically. Considering the time-deceleration mass dependency of the hydraulic system it might behave sensitive to changes in impact speed or the total mass of the sled than the metering pin is calculated for.

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## APPENDICES

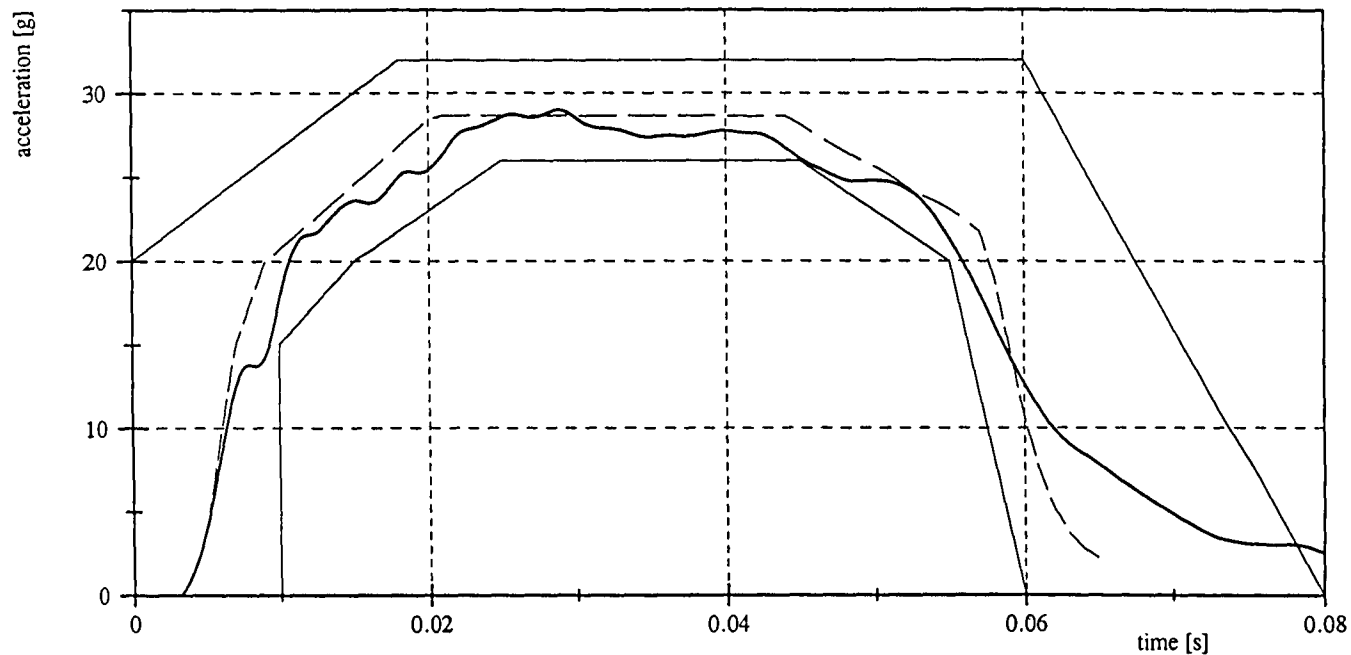


Figure 3. Reproducibility of an ECE-R16 pulse with the HYDRO-BRAKE system. Also included in the figure the minimum and maximum corridors. The dashed line is the wanted, the solid line the simulated curve.

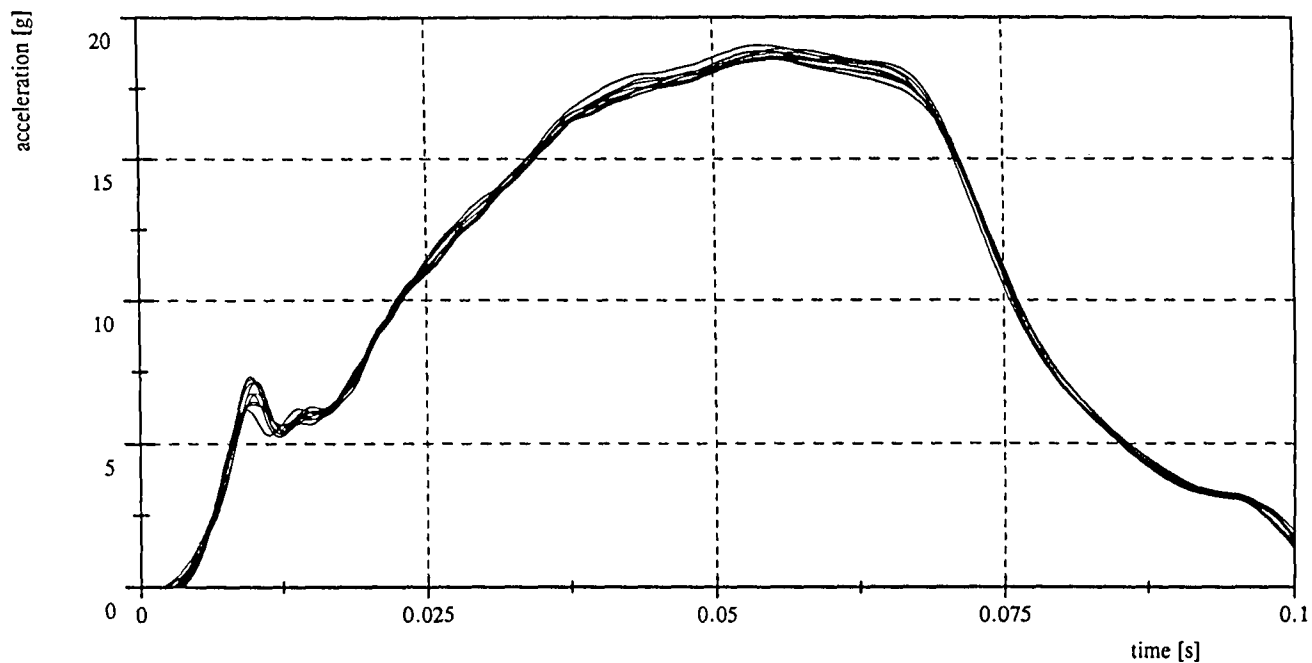


Figure 4. Repeatability of the HYDRO-BRAKE system. Conduction of 10 tests with the same metering pin. Impact velocity 40 km/h,  $\pm 0.1$  km/h.

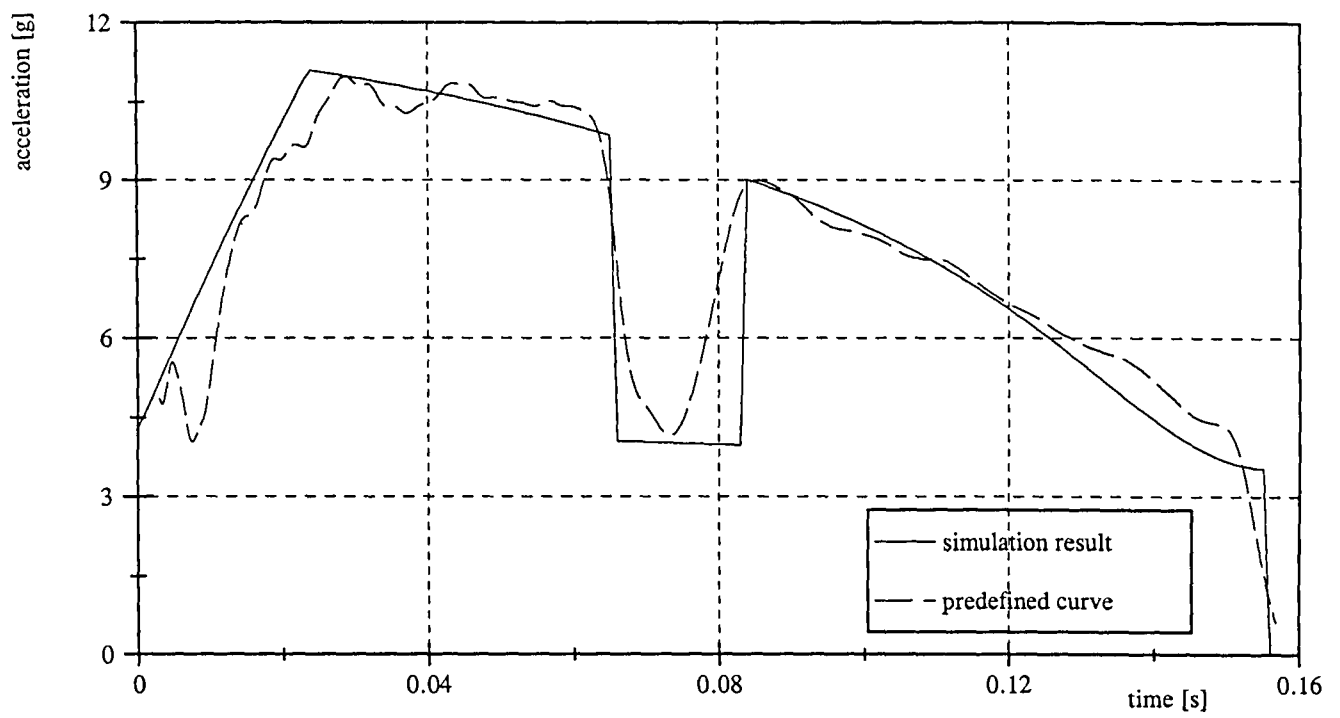


Figure 5. System response to a sudden drop and rise of acceleration

# CALIBRATION OF IMPACT RIGS/ CRASH-WORTHINESS TESTING OF THIN SHEET METAL BOXES

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## ABSTRACT

The present paper addresses the problem of harmonization of crash testing measurement techniques. It involved 14 European laboratories comprising research centres, universities, and the automotive industry, which among them included: 8 vertical drop hammers, 4 horizontal sledges, 1 gas gun, and 1 large-scale Hopkinson bar. The same type of specimens were tested by the different laboratories: extruded aluminum 6063 T7 thin-walled columns of length 400mm. Interesting conclusions were drawn on the effect of signal numerical filtering, the reproducibility of the results obtained from each laboratory, and the overall performance of the rigs at the prescribed impact velocities.

## INTRODUCTION

Dynamic crush characteristics of structural components are currently assessed in impact and crashworthiness laboratories by means of horizontal sledges or vertical drop hammers. Specimens in the form of thin-walled boxes are used. The deformation of these elements can be employed as an energy absorbing mechanism in the case of car collision in order to limit the damage to the passenger compartment, and direct the folding formation and fracture along selected paths. These specimens are sandwiched between an impacting mass  $M_i$  and a heavy anvil of mass  $M_a$ . The specimen is attached to a moving mass (sledge) or to a stationary anvil (drop hammer). In either case the following relationship must hold:  $M_a \gg M_i \gg M$ , where  $M$ =mass of specimen.

The instrumentation for measuring load usually consists of load cells mounted between the anvil and the support plate or accelerometers attached to the impacting mass, together with a corresponding data acquisition system. However, measurement difficulties arise either when testing a single component or, to a larger extent, a complete structure. Separation of the true crash characteristics from the superimposed vibration of the test equipment is a notorious problem in interpreting component or full-scale automobile crash tests [1]. Thus

the various laboratories resort to different filtering techniques.

The present work addresses principally this problem of harmonization of crash testing measurement techniques. It involved 14 European laboratories comprising research centres, universities, and the automotive industry, and it ran for approximately two years. It has shown that the force levels and vibration characteristics recorded on identical specimens by two different laboratories might be different even though similar equipment and similar principles were used.

The main objective of the project has been to perform a comparative study of the dynamic performance of the various types of test rigs for crashworthiness applications and to help calibrate these devices using the JRC large-scale Hopkinson bar as a reference crash test rig.

## EXPERIMENTAL WORK

The results of this project were produced from two rounds of testing (corresponding to two different material batches) conducted by the participating laboratories. The crash tests were performed on triggered column specimens (Figure 1.) of extruded aluminum 6063 T7.

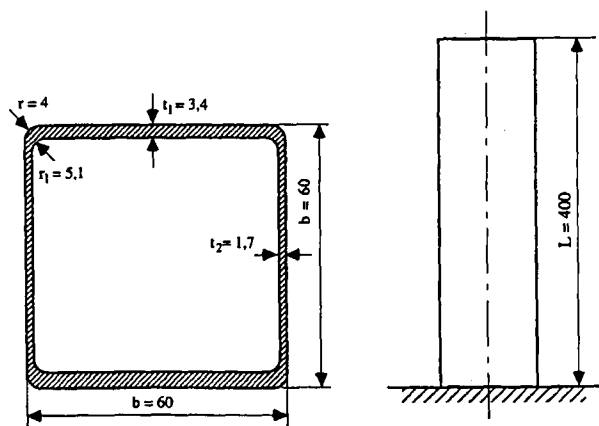


Figure 1. Crash test specimen geometry (dimensions in mm).

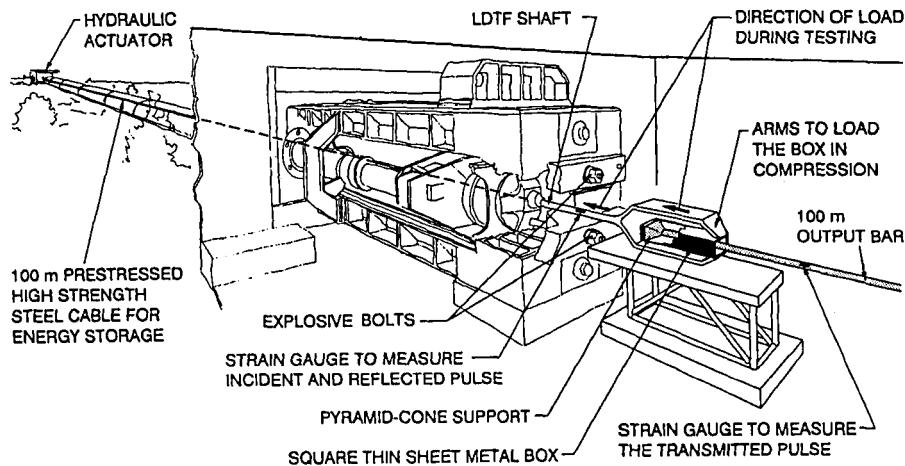


Figure 2. Layout for dynamic crash test at the LDTF.

### Material Testing

The material of both batches was thoroughly characterized on small specimens, cut directly from the thin and thick sides of the above columns. Both quasi-static and high strain rate (1100/s) tensile tests were performed. Three material orientations with respect to the extrusion direction were examined: 0°, 45°, 90°.

These tests have shown some dependence of the mechanical properties on strain rate, specimen orientation and thickness in the elastic region, which, however, disappears in the plastic region. The ultimate stress at strain rate 1100/s is found to be 14% higher than its quasi-static value (low sensitivity, consistent with the literature data). The following average quasi-static values of this Al-6063-T7 have thus been derived: Young modulus  $E=67\text{GPa}$ , yield stress  $\sigma_{0.2}=104\text{MPa}$ , ultimate stress  $\sigma_u=166\text{MPa}$ , ultimate strain  $\epsilon_u=0.10$ .

### Column Crash Testing

The same type of specimens were tested by the different laboratories, which among them included: 8 vertical drop hammers, 4 horizontal sledges, 1 gas gun, and 1 large-scale Hopkinson bar. The dimensions of the

thin-walled column specimens are shown in Fig.1: length 400mm, hollow square cross-section of external dimension 60mm, and thicknesses of opposite sides 1.7mm and 3.4mm, respectively.

Seven tests (designated by the letters A to G) were, on the average, performed by each participating laboratory. The agreed upon test conditions were as follows:

- A, B: Impact Velocity 8.33m/s (30km/h), Impacting Mass: arbitrary;
- C, D: Impact Velocity 8.33m/s (30km/h), Impacting Mass: arbitrary;
- E, F: Impact Velocity 13.88m/s (50km/h), Impacting Mass: arbitrary;
- G : Impact Energy 5300J, Velocity and Mass: arbitrary.

These conditions have practically been imposed by the capabilities available in the laboratories, which differed substantially. For example, it is noted that the common range of impacting mass of 7 laboratories was 500-625kg, whereas the common range of impacting velocity of 8 laboratories was 10-54km/h.

The JRC large-scale Hopkinson bar (called Large Dynamic Test Facility, LDTF) allows the testing and deforming to fracture of large size specimens of high resistance and elongation. Elastic energy is stored in its



100m cables, preloaded by hydraulic pistons. Initially this load is borne by bolts, the explosive rupture of which liberates the energy to propagate as waves to the test piece.

The incident  $\varepsilon_i$ , reflected  $\varepsilon_R$  and transmitted  $\varepsilon_T$  pulses are measured by the two strain gauge stations on the incident and transmission bar (Figure 2.). The application of the uniaxial propagation theory of elastic stress waves along bars having small transverse dimensions with respect to the wavelength of the applied stress pulse [3] allows the calculation of the required parameters. Some of the unique features of this facility include: maximum load =5MN, maximum specimen dimension =3m, maximum specimen deformation =1m, maximum cross-head velocity =40m/s, pulse duration =40ms. In terms of energy applied to the specimen, the LDTF tests can be compared with conventional tests, by equating the elastic potential energy stored in the cable to the kinetic energy of a mass  $m$  attached to the cable end once the bolt has been broken:

$$\frac{1}{2} F \Delta L = \frac{1}{2} m V^2 \quad (1.)$$

where,  $F$ = load of pre-tensioned cable,  $\Delta L$ = elongation of cable and  $V$ = speed of mass  $m$ .

Each laboratory furnished the non-filtered load/shortening recorded signals to the project coordinator. The inter-comparison of the results was made on the basis of the parameters described below [2].

a) **First peak load.** This is the maximum first load of the non-filtered load/shortening curve, denoted by  $P^{\wedge}$ .

b) **Mean crushing load.** Four definitions are applied, where permitted by the laboratory data, on the filtered load/shortening curves. The SAE CFC 180 filter is used.

*Definition I:*

$$Pm1 = \frac{1}{2} M_t V_o^2 / \delta_{fs} = W_i / \delta_{fs} \quad (2.)$$

where,  $W_i$  and  $\delta_{fs}$  are, respectively, the impact kinetic energy and the final shortening of the column, measured after the test.

*Definition II:*

$$Pm2 = \int_{x_1}^{x_1+2nH} P(\delta) d\delta / 2nH \quad (3.)$$

where,  $P(\delta)$  is the load/shortening characteristics,  $x_1$  a suitable reference value,  $n$  an integer and  $H$  the half folding wave length. The integral limits are so chosen as to avoid the uncertainties on the measurement of the first peak load and the last part of the test, where the speed is small and the test is becoming quasi-static. The values employed in the present study are:  $x_1=H=31.6\text{mm}$ ,  $n=1$  and  $n=2$  for lower and higher kinetic energies, respectively.

*Definition III:*

$$Pm3 = \int_0^{\delta_{pm3}} P(\delta) d\delta / \delta_{pm3} \quad (4.)$$

This is the most frequently used method to calculate the mean crushing load;  $Pm3$  is obtained by dividing the area of the recorded load/shortening characteristics by the shortening of the column.

*Definition IV:*

$$Pm(\delta) = \int_0^{\delta} P(\zeta) d\zeta / \delta \quad (5.)$$

where,  $P(\zeta)$  is the instantaneous crushing load when the instantaneous shortening is equal to  $\zeta$ .

c) **Loss energy coefficient.** It is defined as follows:

$$le = (W_i - \int_0^{\delta_{pm3}} P(\delta) d\delta) / W_i = \frac{W_i - W_d}{W_i} \quad (6.)$$

where,  $W_d$  is the deformation energy dissipated by the column.

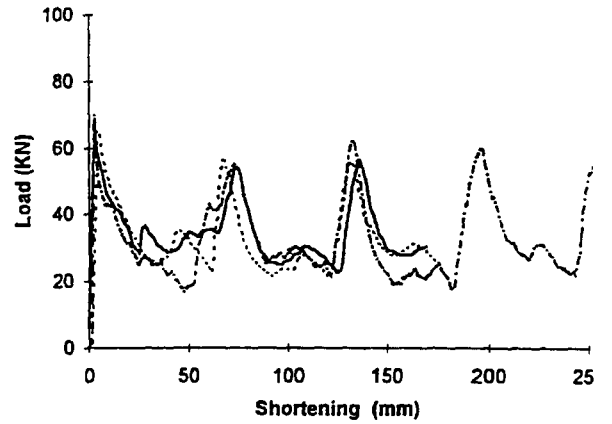


Figure 3. Non-filtered load/shortening characteristics of three static tests.

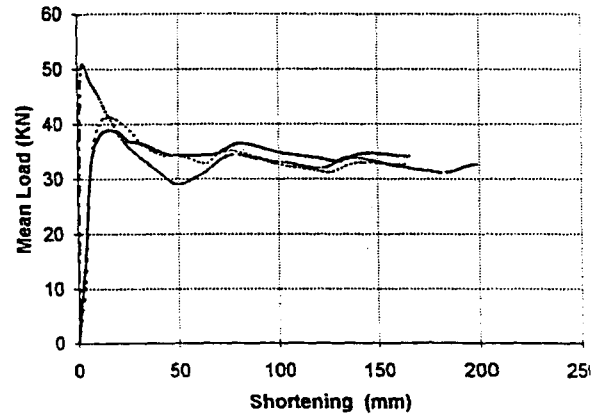


Figure 4. Non-filtered Mean-load/shortening characteristics of three static tests.

**Static Crash Test Results** Five triggered columns were tested under quasi-static conditions by JRC and INRETS. Satisfactory agreement of the results of the two laboratories was observed (Figures 3-4). These tests have produced an average static peak load of  $P^s=68.4\text{kN}$ , and an average crushing wave length of  $2H=63.3\text{mm}$ . These values have been used in calibrating the dynamic tests.

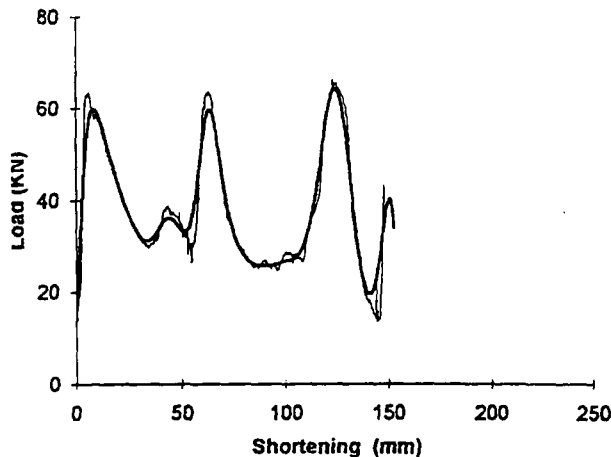


Figure 5. Load/shortening characteristics of test C from transmitted LDTF pulse (— non-filtered, — filtered).

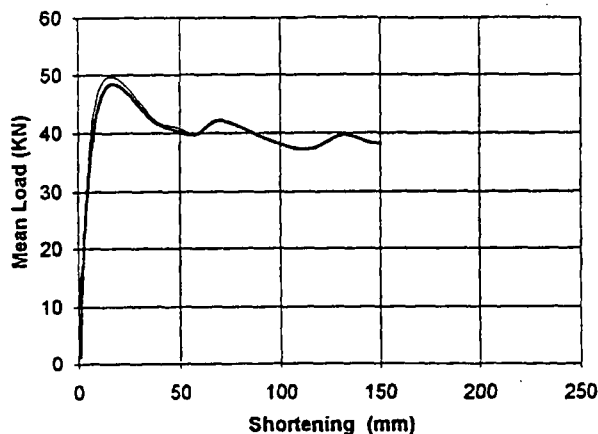


Figure 6. Mean load/shortening characteristics of LDTF test C (— non-filtered, — filtered).

**Dynamic Crash Test Results** The complete set of experimental results, including tables with numerical values and full load/shortening curves of all tests (A-G) for each laboratory, can be found in ref.[2].

For discussion and illustration purposes only six characteristic graphs are reported in this paper. They all refer to test conditions C-D. Figures 5-6 are plots of typical curves obtained from the LDTF tests; the absence of signal contamination is evident. Figures 7-8 are dynamic crash curves produced by a horizontal sledge apparatus, and Figures 9-10 have been produced by a vertical drop hammer device.

Clearly it would be impossible to attempt any comparisons based on non-filtered data. Thus it is recalled that the CFC 180 filter has been employed, and that all comparisons have been performed on parameters derived from filtered characteristics.

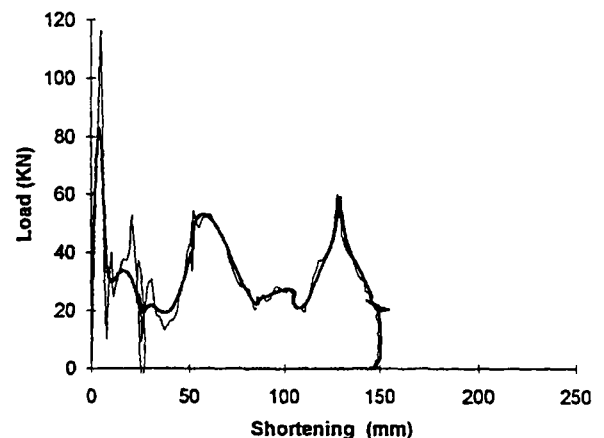


Figure 7. Load/shortening characteristics of test D from a horizontal sledge apparatus (— non-filtered, — filtered).

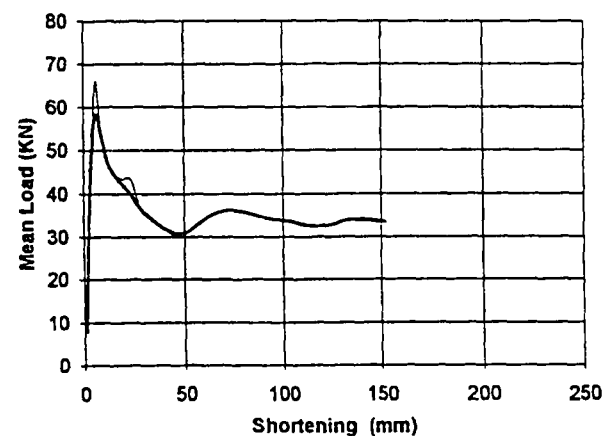


Figure 8. Mean load/shortening characteristics of test D from a horizontal sledge apparatus (— non-filtered, — filtered).

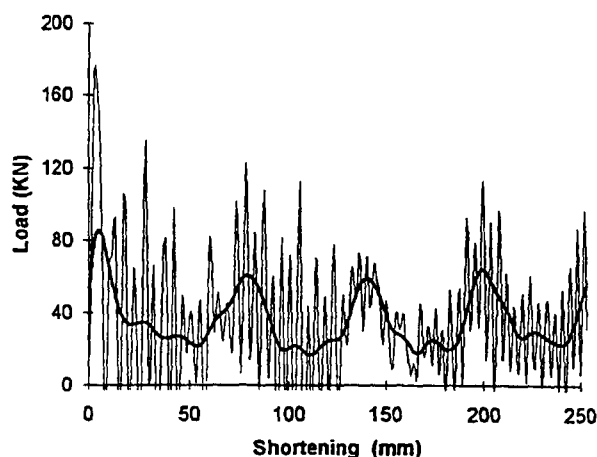


Figure 9. Load/shortening characteristics of test C from a vertical drop hammer device (— non-filtered, — filtered).

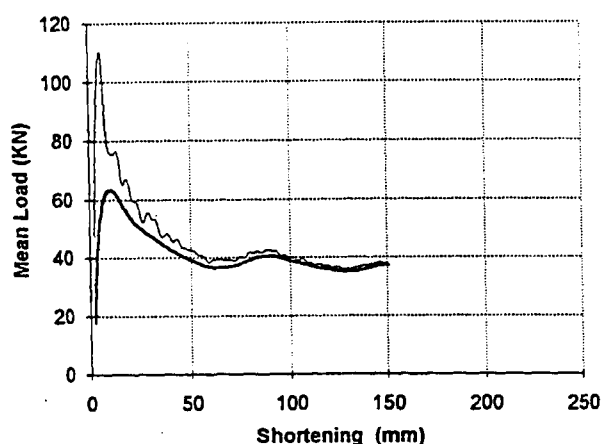


Figure 10. Mean load/shortening characteristics of test C from a vertical drop hammer device (— non-filtered, — filtered).

## COMPARISON OF CRASH TEST RESULTS

Interesting observations have been made on the effects of numerical filtering, the spread of test data from the two batches, the reproducibility of the results obtained from each laboratory, and the overall performance of the rigs at the two prescribed impact velocities [2]. Some parts of them are reported below.

It has been shown that the numerical filter CFC 180 has little effect on the mean load derived from low impact speed tests. For the higher impact speeds the mean load calculated from filtered data is, in general, less than that derived from non-filtered ones. This numerical filter has, however, significant effect on the first peak obtained from horizontal sledges and vertical drop hammers, reducing its value by almost 60%.

The quantification of the spread of the experimental results has demonstrated that all laboratories are capable of performing reproducible crash tests. Only the spread of the first peak load appears to be relatively large (15%).

The two batches of aluminum present an average difference in the column crushing force by approximately 6.5%; a similar difference was also evidenced in the tensile specimen testing.

Regarding the effect of the impacting mass, it has been established that no significant differences exist between the mean forces related to the mass magnitude for the velocities around 30 km/h. This difference becomes, however, more pronounced for the tests at 50 km/h. In this case the tests performed with small masses give higher mean crushing forces, probably because of increased rebound effects.

From the comparison between dynamic conventional and LDTF tests, the high quality of the LDTF measurements has emerged and these results were adopted as reference. The degree of deviation from these values of a particular crash parameter for a given test rig may indicate a need of performing an appropriate calibration procedure. As was recognized, the fundamental advantage of this technique derives from its effective accounting of the dominant phenomenon of wave propagation and the underlying well-founded Hopkinson bar theory

## CONCLUSIONS

This study of column dynamic crushing, carried out by the several laboratories with the different equipment, has produced interesting results. They concern the effect of numerical filtering, the spread of test data from the two batches, the reproducibility of the results of each laboratory, and the overall performance of the rigs at the prescribed impact conditions. Further, the efficiency and precision measurements of the LDTF (large-scale Hopkinson bar) were established and adopted as reference.

A point which is considered to require further investigation is related to the magnitude of the first peak load due to its consequences in the safety of the vehicle occupants. The crush tests of longitudinal beams should be performed with enough energy to reproduce the same strain rate in the material as in real car accidents. Attention is also drawn to the fact that materials, like carbon steel and high strength steel, often show an initial peak in their stress-strain curve at high strain rates, which can generate

a significant first peak load in the load/shortening characteristics of a longitudinal beam.

#### ACKNOWLEDGMENTS

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